

# Tailoring Green Stormwater Infrastructure to Hawaiian Landscapes

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# Table of Contents

<b>Introduction.....</b>	<b>3</b>
<b>Literature Review.....</b>	<b>4</b>
Conceptualizing Hawai`i's Ecological Framework.....	7
Freshwater and Land Use in Hawai`i.....	15
Runoff, Environmental Degradation, and Public Health.....	20
Projected Impacts of Climate Change in Hawai`i.....	23
A New Paradigm of Stormwater Management.....	28
<b>Analysis and Methods.....</b>	<b>34</b>
Analysis.....	34
Methods.....	35
Assumptions and Metrics.....	37
<b>Results.....</b>	<b>38</b>
<b>Interpreting the Results.....</b>	<b>61</b>
<b>Policy Recommendations.....</b>	<b>62</b>
<b>Concluding Thoughts.....</b>	<b>65</b>
<b>Resources.....</b>	<b>67</b>

## Introduction

As the future brings uncertain conditions around the globe, every region must make customized decisions to anticipate change and modify aging infrastructure to meet the challenges of a new climate. Terrestrial and oceanic warming, changing weather patterns, increasingly extreme storms, and ecosystems in transition will test all communities and confront local officials to lead with great creativity and resourcefulness. An infusion of scientific understanding and decision-making into local policy creation—testing, trial, error, and incremental implementation—will help localities to adapt.

Transition and evolution are intrinsic to every stretch of the globe, but the rapid changes brought on by global climate change will test even the hardest natural systems. In the effort to transition towards resilience, some areas will face greater threats than others. Resource-limited, isolated, and vulnerable to the slightest of change, islands like Hawai`i will serve as a barometer of future adaptation and innovation potential. As a result of marked differences in microclimates due to physical geography and the impacts of the built environment, Hawaiian regions experience drastically different rainfall volumes and intensities. Global climate change is projected to magnify both the over abundance and lack of water in Hawai`i. Forthcoming uncertainty surrounding storm intensity and duration calls for specialized solutions with a wide margin of error.

This analysis was conducted in an effort to more comprehensively understand Hawai`i's current and prospective issues with water, encourage site-specific water management solutions based on the analysis of unique local conditions, and provide

management recommendations for environmental planning in the time of global climate change. The following study begins with a literature review summarizing the state's unique local conditions, historical relationship with water, and specific concerns, then reviews the evaluation of several experimental sites on the island of O'ahu, and finally draws policy recommendations from a localized analysis. This study provides foundational suggestions for the consideration of stormwater management as local and condition-specific. By increasing the ease of site analysis for alternative stormwater management regimes, GSI may become a more common practice, thereby reinforcing its efficacy through regional implementation.

## Literature Review

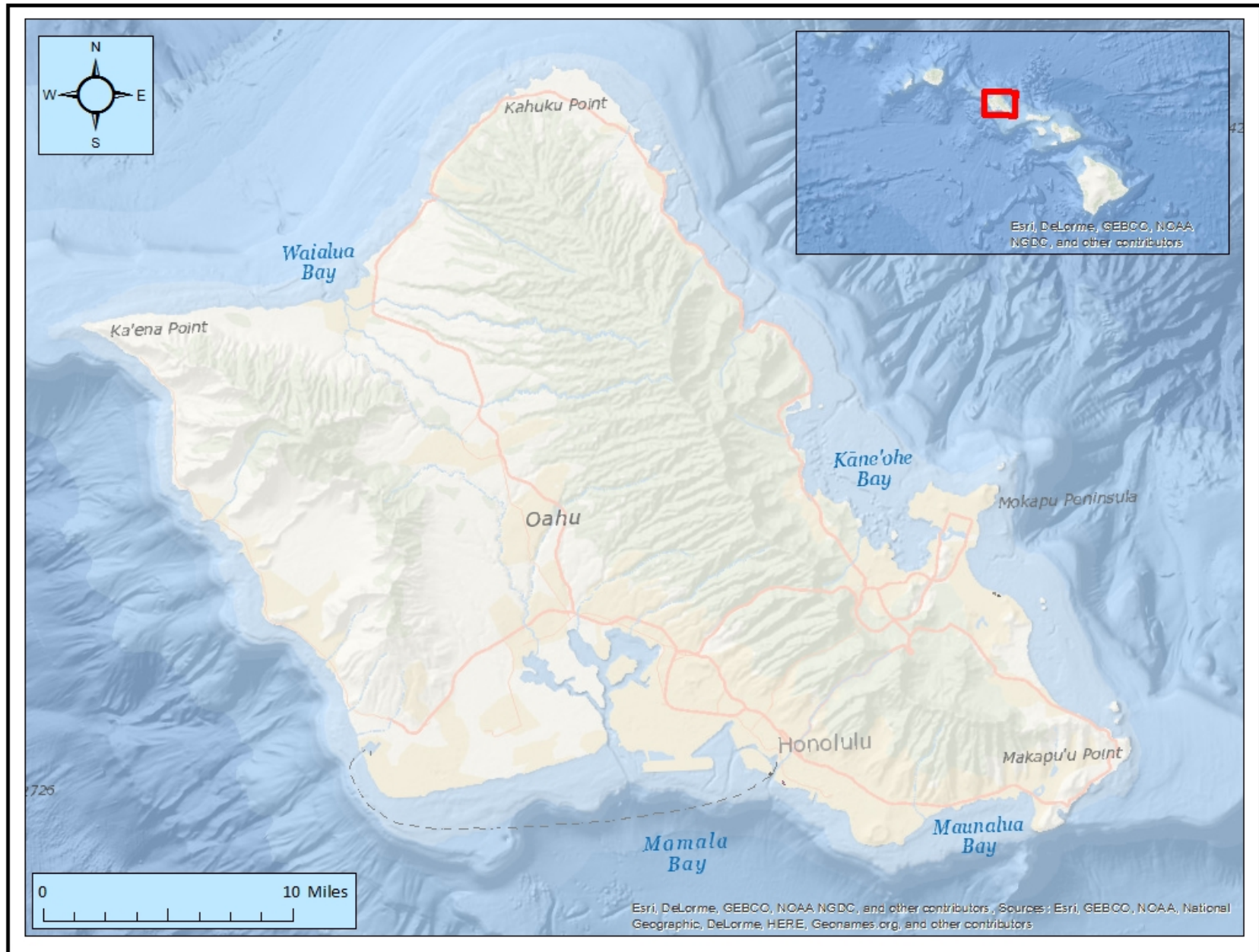
Alterations to the natural world during the construction of the built environment have led to stormwater issues in Hawai'i. Seemingly conflicting issues, flooding and water scarcity, are paramount concerns throughout the archipelago, particularly as the isolated island chain faces the threat of global climate change. As innovative stormwater practices begin to be adopted from the continental United States, unique Hawaiian conditions must be considered in their implementation.

This literature review seeks to illuminate these circumstances and provide a foundation for the application of effective green stormwater management solutions in Hawai'i. First, an examination of Hawai'i's evolution and ecology will explain the original form of stormwater 'management' in the islands. Following this discussion, alterations to the natural world and the



subsequent impacts of anthropogenic influences on urban stormwater will be examined. These shifts in the natural balance of stormwater will then be viewed in the context of both human and environmental impairment. Finally, an assessment of climate change predictions for the state of Hawai`i will forecast the potential amplifications of stormwater issues in the future. This review will serve to inform the appraisal of stormwater interventions that have been applied within Hawai`i to date, and provide evidence for future policy decisions to better tailor stormwater management solutions to the environments and communities they serve.

## O'ahu's Geographic Position in the Hawaiian Archipelago

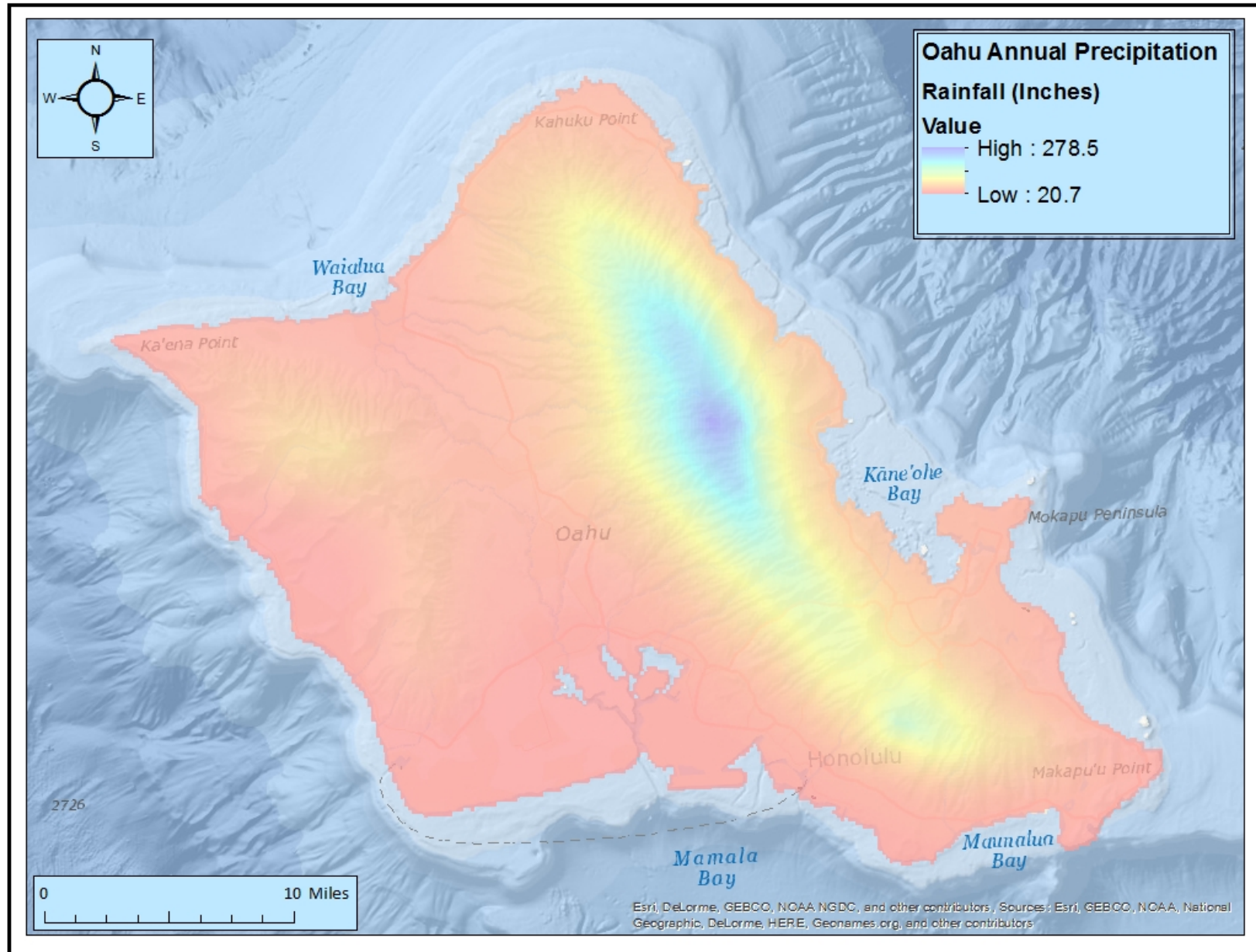


## Conceptualizing Hawai'i's Ecological Framework

Hawai'i is generally regarded as a lush tropical paradise, but few realize the tremendous diversity of landscapes the islands play host to. Snow capped volcanic craters, arid coastal plateaus, and one of the wettest spots recorded on the earth are all found in Hawai'i. The state owes this mosaic to its unique geologic make-up, which combined with the forces of time and weather, transformed the chain of islands into one of the most distinctive places on the planet.

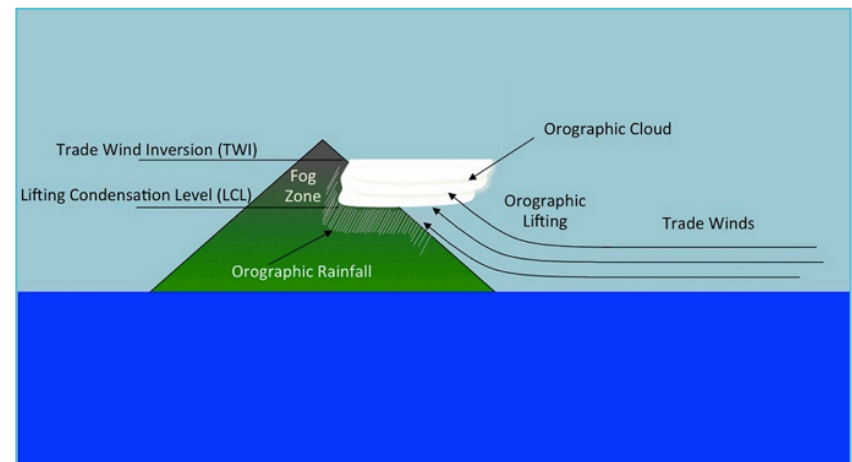
If the Hawaiian Islands had not formed in their present location, the ocean where they are currently situated would receive about 25 to 30 inches of rain per year. Instead, the most isolated archipelago in the world intercepts an average of 70 inches of rainfall per year from the air (Western Regional Climate Center, n.d.). This disparity is the result of the state's volcanic landforms, which extend towards the sky and disrupt the flow of air and moisture across them. This phenomenon, orographic precipitation, has resulted in the evolution of commanding landscapes and disparities in precipitation across the islands.

## O'ahu's Annual Precipitation



Hawaiian precipitation is characterized by the forced lifting of air over mountain slopes, orographic lifting. This process moves unsaturated air upwards, resulting in cooling, and ultimately the creation of water vapor. As orographic lift occurs, the formation of water vapor, 'saturation', forms clouds at the lifting condensation level. Eventually saturated air undergoes condensation, the phase change of gaseous water vapor to liquid water. This occurrence causes the deposition of excessive precipitation on the 'windward' side of a mountain and a dry 'rain shadow' effect on the 'leeward' side of the same mountain.

Orographic precipitation often occurs in areas with a steady wind source over warm oceanic waters. Hawai'i's persistent northeastern trade winds result in precipitation falling on the windward sides of Hawai'i's mountainous areas year-round. Rainfall is heaviest on the mid-slopes of the mountains, eventually sheering off due to a trade wind inversion. The trade wind inversion halts rising, cooling air at about 7,000 feet above



Orographic Precipitation

sea level, redirecting its flow around the mountain, rather than upwards. As a result, high-altitude areas of Hawai'i are among the driest areas found on the islands (Rainfall Atlas of Hawai'i, 2011). In addition to wind-driven lifting, the air around the Hawaiian Islands also rises as it is heated through the process of convection. Convective lift most often occurs in the central portions of the islands, and also results from the influence of sea breezes on days when trade winds are absent.



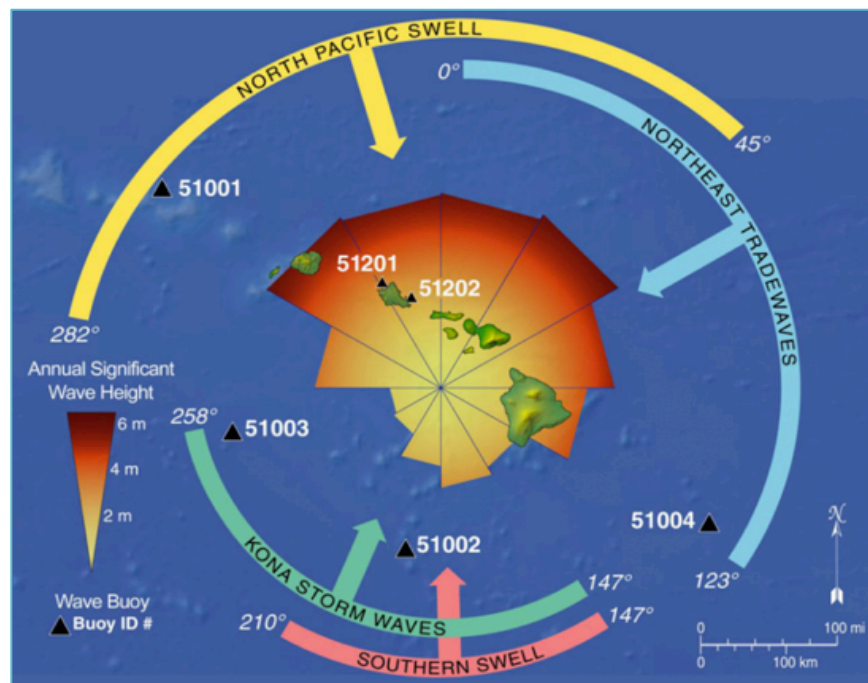
Orographic precipitation results in profound disparities in the geographic distribution of rainfall. Despite the islands' average of 70 inches of rainfall per year, some mountainous areas of Hawai'i receive rainfall of over 240 inches per year (20 feet). The highest recorded average falls on Mount Waialeale, Kaua'i, which receives over 480 inches (40 feet) of rainfall each year. The peak of Mount Waialeale is 5,000 feet above sea level, below the trade wind inversion layer, and is the receiving area of the highest recorded average rainfall on earth (Western Regional Climate Center, n.d.). The highest altitude areas of Hawai'i, such as Mauna Kea and Mount Haleakalā receive only 8 to 40 inches of rainfall per year due to their location above the trade wind inversion point.



*Mount Waialeale (5,000 feet above sea level) and Mount Haleakalā (10,000 feet above sea level). The trade wind inversion layer occurs at 7,000 feet above sea level.*

Hawai'i has two seasons, Kau wela, summer, (May-October) and Ho'oilō, winter, (October-April) (Oki, n.d.). The seasons generally dictate the distribution and intensity of rainfall around the archipelago. During El Niño events regular seasonal patterns are thrown into disarray, often resulting in drought conditions throughout the state and an increased frequency of hurricanes and tropical storms (Guidry and Mackenzie, n.d.). Kau wela is characterized by warm, consistent trade winds, while Ho'oilō has weaker

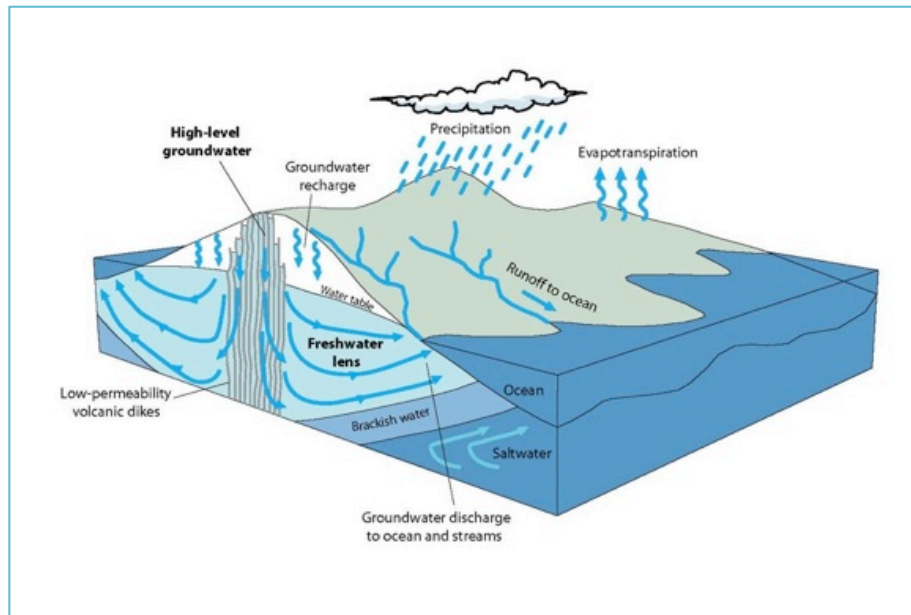
trade winds, allowing winter storms to cross the islands. Leeward lowlands around the state, which are situated in the orographic rain shadow, receive as little as 8 inches of rainfall per year (Rainfall Atlas of Hawai'i, 2011). These areas receive most of their rain through weather events such as cold fronts, Kona storms, and tropical disturbances, which interrupt the trade wind inversion layer and allow for widespread rain. A distinct annual rainfall cycle brings higher rainfall to the leeward areas during the winter season (October-March) due to such disturbances. Because leeward regions receive large inputs of rainfall over short periods of time, flash flooding is a predominant issue associated with precipitation in these areas.



Hawaiian Seasonal Variations

A lack of percolation during storm events, due to both natural characteristics like soil moisture and the impervious nature of the built environment, consistently leads to issues with stormwater runoff. Leeward lowlands are often the most highly urbanized areas around the state, leading to a rampant disparity in freshwater availability where it is needed most.

Hawaiian residents rely on a fragile basal 'lens' of potable groundwater that lies beneath each island. This fresh water is among the most pure in the world, having percolated from the surface through a natural filtration system of porous volcanic rock



The Freshwater Lens

and accumulated over millions of years. Because freshwater is less dense than saltwater, freshwater stores 'float' below each island, separated from seawater by a mixed layer of brackish water (Leong, 2015). Fresh water also extends above sea level as well, stored in the island's porous, sponge-like lava rock. While researchers continue to define the extent of freshwater stores in the islands, one fact remains certain—the supply of freshwater in Hawai'i is finite. Hawaiian groundwater is used for 99% of drinking water and 50% of other freshwater uses (Gingerich

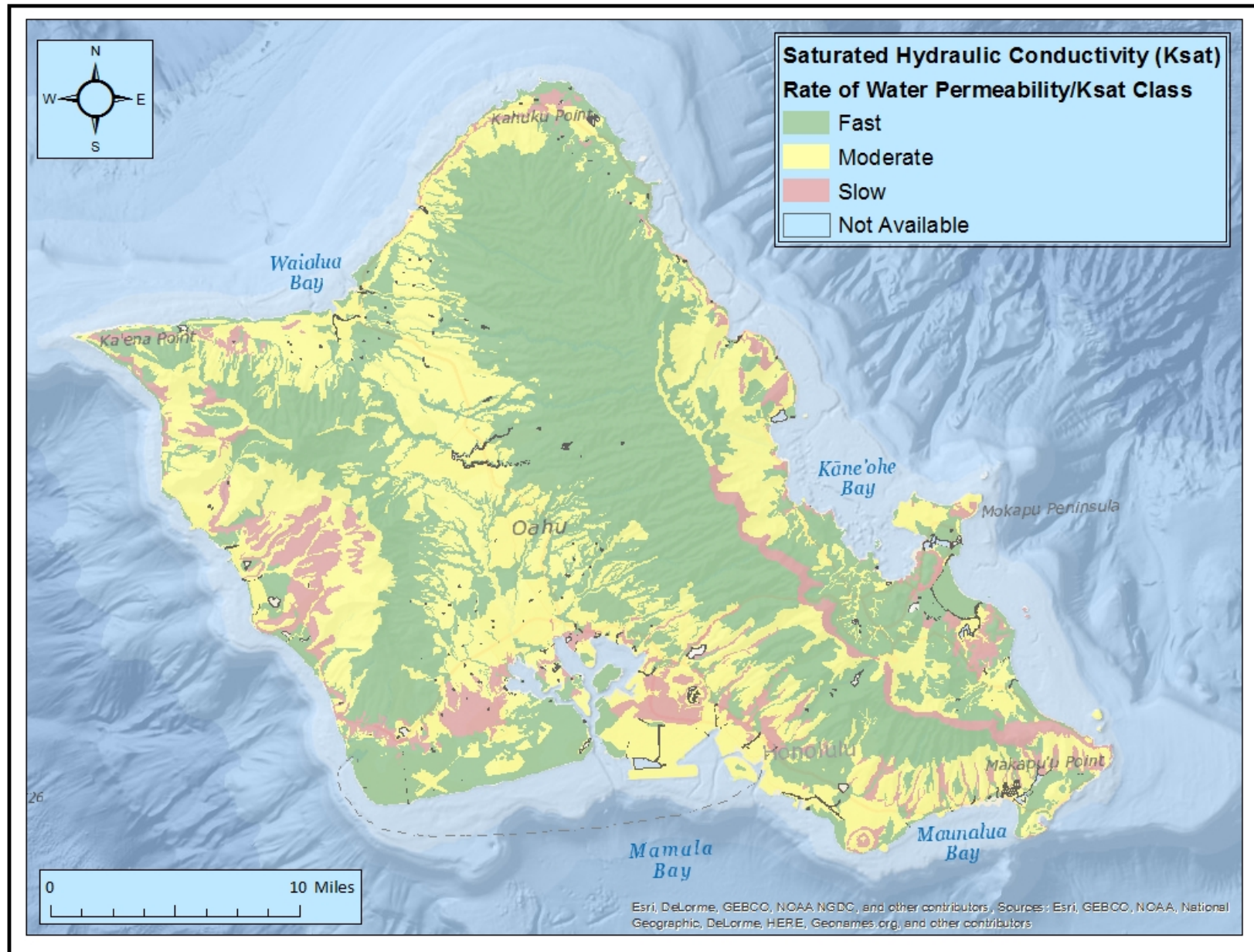
and Oki, 2000). Hawai'i's most urbanized island, O'ahu, consumed about 145-150 million gallons of fresh water per day in 2014. Despite the state's incredible reliance on groundwater stores, about a third of daily precipitation is lost to the ocean as runoff (Leong, 2015).

Soil conditions, though hidden from plain sight, are one of the most important factors guiding groundwater recharge rates.

Despite a relatively small total land area of 6,420 square miles, the state is host to ten distinct soil orders. Like Hawai'i's weather patterns and vegetation, soil zones vary starkly over short distances. Soils evolve just like other natural landscapes, and are beholden to the influence of time, weather, geologic processes (parent materials), slope, drainage, temperature, vegetation (organic matter), and local rainfall (Lau and Mink, 2006). While there are only six types of soils on the relatively young 400,000 year old Big Island of Hawai'i, 5 million year old Kaua'i is home to more diversity, with ten types (Blay and Siemers, 2004, Deenik and McClellan, 2007).

Soils have been coded in a classification system to enable soil order comparisons and evaluate drainage. These soil types can be leveraged as a means to compare interisland percolation and recharge conditions. As such, the same soil type on two different islands will have formed under similar conditions, and will respond similarly to local weather phenomena. Soil structure and porosity contribute to overall permeability. Hawaiian forest soils exhibit the highest value of water retention, 28%, and porosity, 66 to 90%. Agricultural and pasturelands exhibit the lowest rates of water retention, 19%, and porosity, often lower than 8% (Lau and Mink, 2006).

## O'ahu's Soil Permeability





Hawaiian drainage basins, or watersheds, are very small in area compared to other mountainous regions. Small basins contribute to flooding due to prior wetting, storm intensity, and urban land use (Lau and Mink, 2006). Variables impacting runoff include rainfall amount and intensity, soil permeability, slope gradient, water table height, vegetation, and soil moisture. Each of these characteristics varies throughout the Hawaiian Islands, particularly on the leeward and windward sides of the islands. Dramatic rainstorms can also occur irrespective of orographic effects throughout the state. Yet, the areas with the highest average rainfall do not necessarily have the most torrential storms. In fact, dry leeward areas can receive almost all of their mean annual rainfall in a single day.

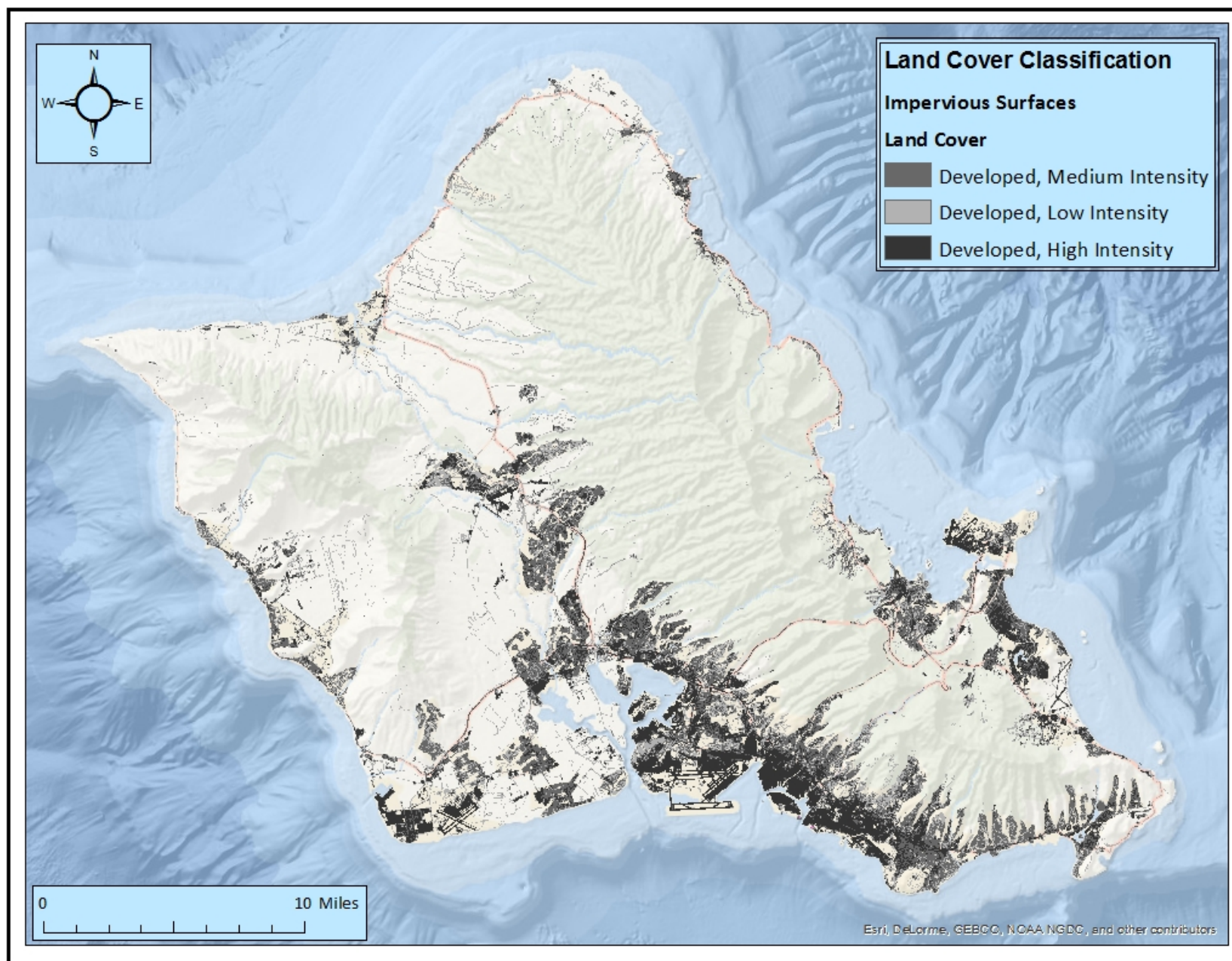
### **Freshwater and Land Use in Hawai`i**

Land use has a tremendous influence on flooding in Hawai`i. In a natural system, stormwater falls in vegetated areas and collects on plants, in the soil column, and at natural low points. At the point of saturation, runoff sluggishly flows just below the ground surface. Some subsurface flow infiltrates to recharge the aquifer, while the remainder moves laterally towards tributaries and rivers, and eventually, the ocean. Robert Horton (1875-1945), regarded as the father of modern hydrology, described the concept of overland flow as flooding produced when rain intensity exceeds the infiltration capacity of the soil (Horton, 1933).

Runoff is heightened after periods of drought, when soil is dry and unable to efficiently percolate, or following excessively wet periods, when soil is saturated and unable to accept additional moisture.

Anthropogenic alterations to hydrologic features of the landscape, 'hydromodifications', have impacted the environment's natural ability to process stormwater. Subsurface flow, a critical component of the water cycle, is disrupted by the construction of impervious surfaces such as asphalt roadways and building rooftops, reducing natural storage capacity. Overland flow increases in urbanized areas with impervious surfaces, in areas with low vegetation cover, and in arid and semi-arid areas. Studies have shown that 'Hortonian' overland flow is rare in vegetated or humid areas, but increases in steep, saturated areas (Lau and Mink, 2006). The proportion of stormwater that results in runoff is different in every watershed, varying temporally from as little as 5 to over 50% of rainfall (Oki, n/d.).

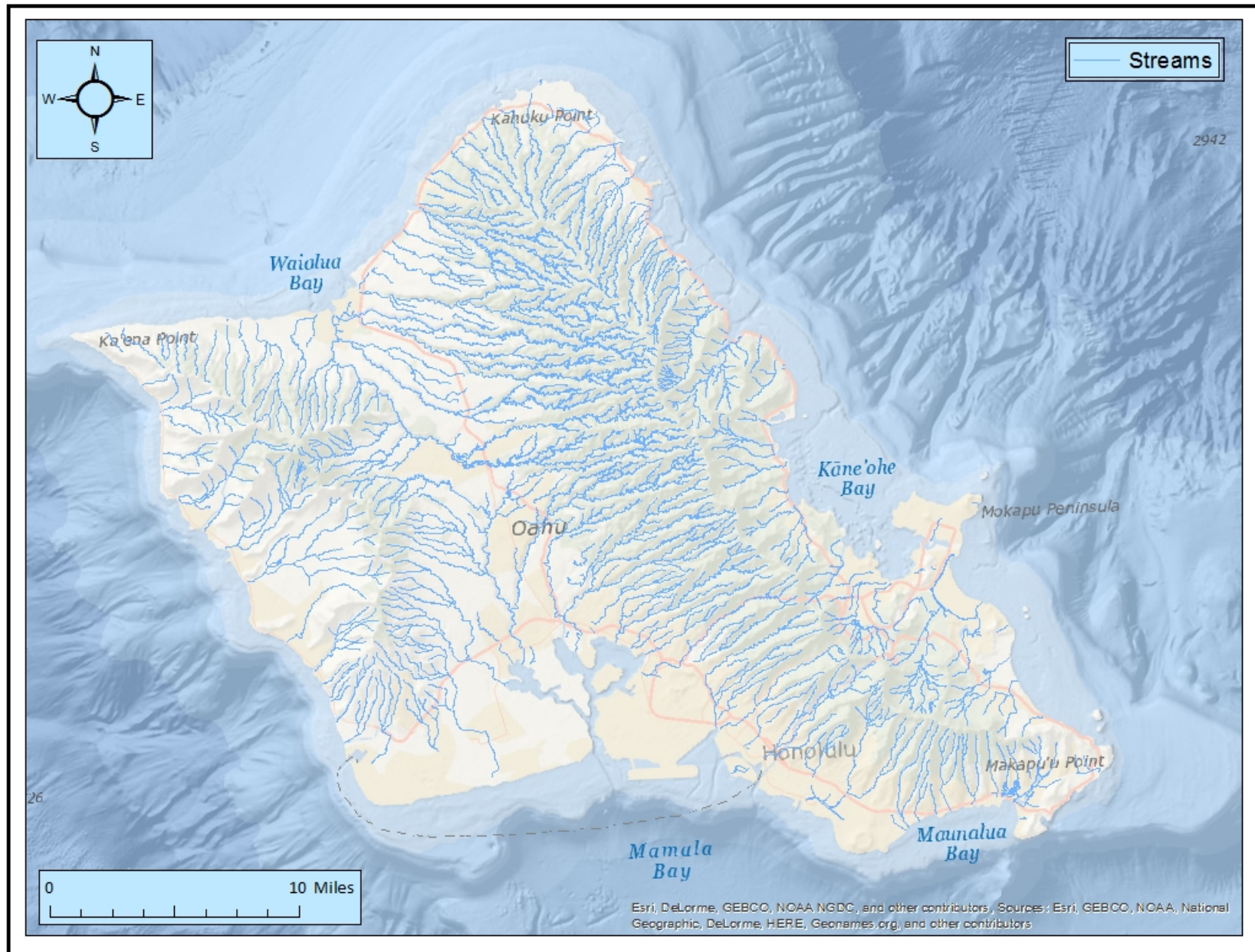
## O'ahu's Impervious Surface Land Cover



Following rapid urbanization in the 1950s, flooding issues in O‘ahu were addressed through structural amendments in the form of storm-drainage facilities. High land prices in Hawai‘i reduced the feasibility of using large reservoirs to store excess water. Instead, urban drainage facilities like channelized concrete waterways were constructed to mitigate floodwaters in urban areas. As of 1988, an estimated 14% of Hawai‘i’s perennial streams (streams that contain water year-round) were in ‘pristine’ condition (Stone, 1988). By 1990, approximately 20% of the state’s 376 streams, over 100 miles of stream area, were documented as channelized (Hawai‘i Stream Assessment, 1990). Channelization projects remove heterogeneous substrate and stream banks, alter flow patterns, and reduce channel migration. As of 1990, virtually every stream on the island of O‘ahu was lined or straightened (Hawai‘i Stream Assessment, 1990).

The landscape-scale process of urbanization, facilitated by the reach-scale channelization of streams and removal of riparian canopy cover, has resulted in microhabitat-scale alterations, such as substrate, temperature, and water composition changes (Brasher, 2003). Though channelization was intended as flood control, alteration projects have had many unintended and poorly understood consequences. The built environment generally diverts stormwater runoff into channelized ditches and streams, increasing both the flow-carrying capacity and flow speed of water (Brooker, 1985). These diversions elevate water volumes and ‘peak discharges’ in urban areas as compared to their rural counterparts (Konrad, 2003).

## O'ahu's Freshwater Streams





‘Flashy’ floodwaters in Hawai‘i were once mitigated by floodplains and wetland systems, however many of these ecosystems no longer exist. Flat, buildable land is scarce in the state due to the steep nature of the archipelago’s dominant landforms, mountainous volcanic formations. As a consequence of 19<sup>th</sup> and 20<sup>th</sup> Century urbanization, state-wide wetland loss amounts to 15%, ranging from 6 to 8% loss on Maui, Moloka‘i, Hawai‘i, and Kaua‘i to 65% loss on O‘ahu (Van Rees and Reed, 2014). Today, wetlands cover less than 3% of the state’s surface area (Association of State Wetland Managers, n.d.). In coastal lowlands, the impact of wetland loss has been most severely felt; compared to 3% of relatively high elevation wetlands, 44% of coastal wetland areas have been lost (Van Rees and Reed, 2014). Though wetlands have been drained and filled to accommodate development, they remain relatively low areas where water naturally collects. Construction in these areas is therefore at risk of damage from storm events, while simultaneously elevating the risk of flooding outside of the historical floodplain.

### **Runoff, Environmental Degradation, and Public Health**

Land use modifications are not only associated with increases in water quantity, but are also associated with a decrease in the quality of water. The concept of ‘first flush’ is associated with the polluted initial quantities of stormwater, with storm water quality improving after accumulated pollutants are washed from the system. For instance, if a storm comes through a community after months of drought, the roadway will be filled with pollutants and litter accumulated over the drought period. Built up levels of

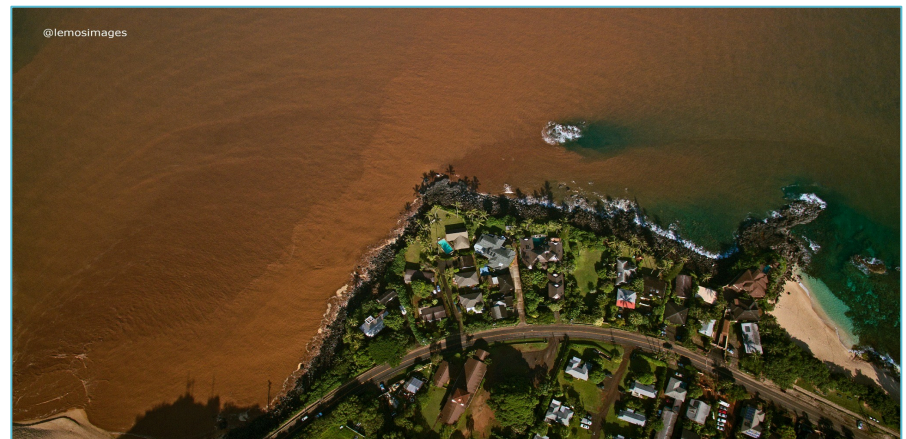
anthropogenic pollutants, such as heavy metals and hydrocarbons, as well as organic nutrients like nitrogen and phosphorous, are washed away in the first flush. These pollutants, combined with fertilizers, pesticides, herbicides, and pathogens threaten coastal environments as they make their way to the sea (Storlazzi et al., 2009). The contaminants within first flush pollutants degrade near-shore ecosystems and threaten the health of beachgoers.

Point-source discharges of water have vastly improved since early 20<sup>th</sup> Century waste management practices, which involved the discharge of untreated sewage at shallow depths, leaving visible plumes of waste. Today, non-point sources pose the greatest threats to coastal waters. Coastal dead zones discovered off the Kohala coast of Hawai'i have been attributed to intense localized flash flooding, delivering thick brown muck to centuries-old coral reef ecosystems, blanketing them in nutrient-laden non-point source waste (Wilson, 2009). The Ala Wai canal on O'ahu is a chief 'source' of non-point pollutants entering near-shore ecosystems. Runoff from the Ala Wai basin drains into the canal, which was excavated as a mechanism for wetland drainage, not stormwater management. Despite its direct adjacency to the important tourism hub of Waikiki Beach, the Ala Wai contains fecal indicators and pathogens in high concentrations.

The inundation of coastal areas by terrestrial stormwater threatens environmental integrity, public health, and the local economy. Coral reefs, one of the largest tourist attractions in Hawai'i, are resilient to the waves and storms but often fall victim to anthropogenic impacts. Both sedimentation and nutrient loading via terrestrial runoff are mitigated in areas with wave action. Without the natural flushing action of waves, areas like bays and lagoons are susceptible to eutrophication and sedimentation. A

study in Hawai'i found that coral cover, diversity, and species richness had an inverse relationship with human population settlements within 5 kilometers (3.1 miles) (Jokiel, 2006). Natural disturbance and recovery cycles within coral communities have been amplified and curtailed by anthropogenic influences. As such, along with biological dynamics, anthropomorphic stressors have been identified as an important force in modern-day Hawaiian coral reef community structure.

The coastal surface waters of Hawai'i are warm and largely oligotrophic (Lau and Mink, 2006). Freshwater inputs, especially polluted discharges, can have detrimental impacts on near-shore ecosystems. In extreme cases, stormwater runoff can lower salinity for a period of several days, producing an environment deadly to coral. Additionally, nutrients transported by floodwaters can spur the growth of phytoplankton and algae blooms, and sediments deposited by floodwaters can increase turbidity and limit the ability of the algae zooxanthellae, which live within corals and provide their pigmentation, to photosynthesize. These factors present relentless challenges to near-shore systems, and often occur concurrently as a result of inland flooding.



O'ahu Brown Water Advisory, 2016

Compounding non-point source runoff issues, Honolulu has a history of sewer failures due to aging infrastructure. Hawai'i utilizes a combined sewer system, which collects sanitary sewage and stormwater runoff in the same pipes. Combined sewer

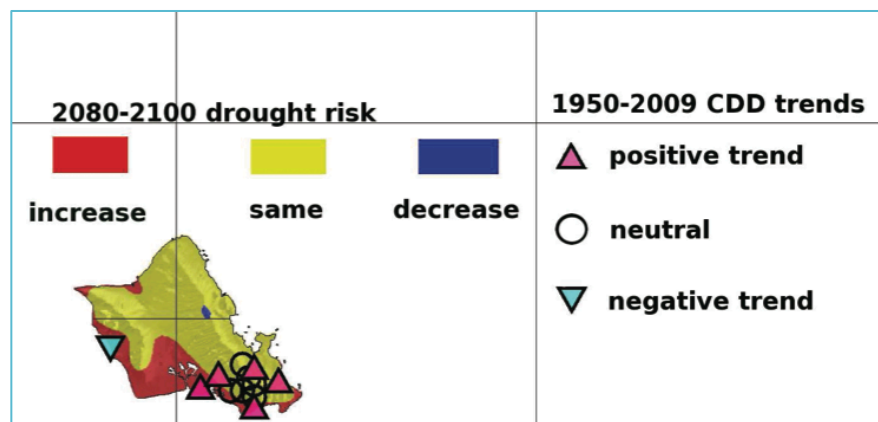
overflows, which result in ‘brown water’ advisories, occur during drastic fluctuations in weather, like severe storm events. Honolulu has a history of combined sewer overflows; a spill in 2006 resulted in the release of 50 million gallons of sewage into the Ala Wai Canal near Waikiki Beach (Dingeman, 2006). As a result of this notable system failure, the City and County of Honolulu entered into a consent decree in 2010 with the U.S. Environmental Protection Agency (EPA). The consent decree resulted in the commitment of billions of dollars in upgrades to the city and county’s municipal wastewater system to avoid raw sewage discharges. In March of 2016, Hawai‘i was the last state to ban cesspools, a waste disposal method that concentrates raw sewage underground with no treatment (Wiens, 2016). The state has about 88,000 cesspools on record, which inject an estimated 55 million gallons of raw sewage into Hawai‘i’s groundwater every day (Maui County, n.d.). Eutrophication from stormwater runoff can increase incidences of offshore algal blooms and allow for the invasion of exotic species, both of which are damaging to Hawai‘i’s tourism economy.

### **Projected Impacts of Climate Change in Hawai‘i**

While each of the Pacific’s 30,000 islands are vulnerable to climate change, the extent of each landmass’ vulnerability is contingent on a combination of geologic composition, land area, elevation, coral reef coverage, and aquifer size. As the global climate continues to change, the management of Hawai‘i’s water resources has become more important than ever. Climate

extremes are projected to increase in the state, likely resulting in persistent stormwater issues. The Hadley HADCM2 model predicts that Hawaiian rainfall will increase for both short-lead (2025-2034) and long-lead (2090-2099) simulations during the summer months. The Hadley model anticipates no precipitation changes for the winter months. Other scenarios from the Special Report on Emission Scenarios (Scenarios A2 and B2) project no mean precipitation change for the state between 2071-2100, but project an increase of 0.12 to 0.16 inches per day for long-lead in precipitation for the summer months, corresponding to an increase of 10.8 to 14.2 inches during June, July, and August in the period of 2090-2099 (Guidry and Mackenzie, n.d.).

The application of global climate models (GCMs) like the Hadley HADCM2 to small regions may not represent fine-scaled, orographically influenced topography accurately. Scaled down climate models have attempted to capture Hawai'i-specific climate



Observed Changes in O'ahu's Precipitation

scenarios. Some state-specific modeling predicts that storms are expected to intensify in orographically influenced windward areas and decrease in leeward regions dependent on convective rainfall (Hamilton, 2014). Other climate models anticipate a 5-10% decrease in wet-season precipitation and a 5% increase in the dry season (Timm and Diaz, 2009). Recent trends have shown an increase in leeward rain, further

complicating management implications. Historical climate data in the state has demonstrated a 'drying trend' over the course of

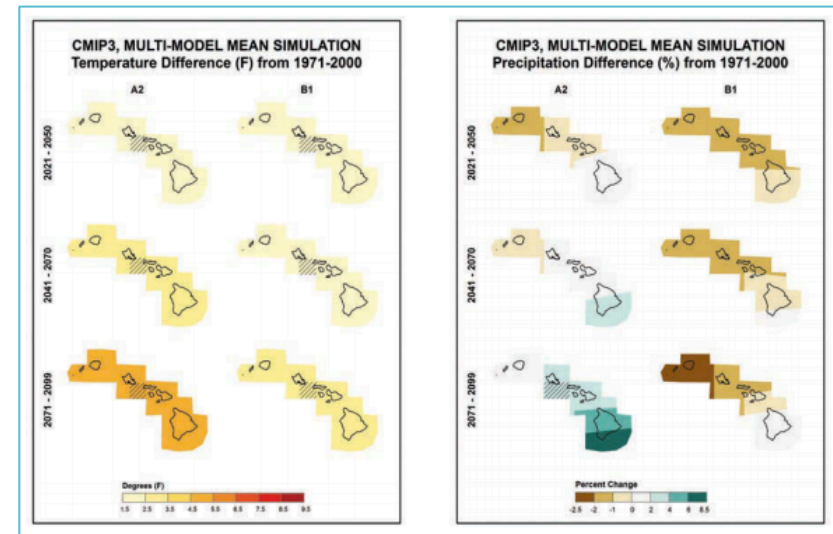


the last century, with a corresponding decrease in stream base flow. Though precipitation models vary, it is clear that the management of intermittent and unpredictable rainwater resources will be crucial throughout the century.

Hawai'i's precipitation models run contrary to the historic record of rainfall, soils, and sediments in the state, all of which indicate elevated precipitation levels in the past have been associated with cooler temperatures. In the near future the impacts of unpredictable storms will be magnified by climbing average temperatures, which are expected to rise between 2.5-4° Celsius over the course of this century. Increasing heat will amplify the state's drying trend by increasing evapotranspiration, particularly in leeward areas (Hamilton, 2014). It is possible that increased evapotranspiration will not be offset by predicted increases in rainfall, leading to potential water shortages.

As the climate warms, trade wind inversion days are anticipated to increase from 80 to 90%, resulting in a decrease in conditions amenable to storm formation in leeward areas (Hamilton, 2014). The increasing intensity of trade winds has

already influenced the Pacific Region—since 1990 trade winds have inexplicably strengthened by up to 50% (Jervey, 2014). Climate scientists believe that over the last two decades strengthening Pacific trade winds have produced a global warming 'hiatus' in the



Projected Temperature and Precipitation Changes

region, caused by increased oceanic heat uptake. This phenomenon, which was not predicted by climate models and has never been observed before, is increasing oceanic upwelling, the process of cool, deep water rising to the surface, and containing more atmospheric heat in the subsurface of the ocean (England et al., 2014). This unprecedented consequence of climate change could lead to further volatile conditions; warmer ocean waters are more hospitable to tropical storm formation and provide unsuitable habitats to many species that have evolved in cooler conditions, like coral reefs. Increasing trade winds may not remain at current levels of intensity; the winds have been attributed to the process called Interdecadal Pacific Oscillation. Scientists warn that the warming being stored in the Pacific will resurface at an unknown time and could occur rapidly (Jervey, 2014).

The freshwater lens that supplies the state's drinking water is dependent on rainfall, making fitful precipitation changes particularly alarming. As sea level rises, a reduction in the freshwater lens will allow saltwater and brackish water to intrude upward and landward, resulting in saltwater inundation of coastal springs and wells (Gingerich and Oki, 2000). A reduction in stream base flow, saltwater inundation, and changing precipitation patterns all pose threats to the availability of freshwater in Hawai'i's future. Groundwater withdrawals amplify all of these issues, further reducing stream base flow, allowing for increased saltwater intrusion, and relying on unpredictable rainfall for freshwater recharge.

Other anticipated impacts have implications for the availability of freshwater as well. A doubling of coastal erosion rates is predicted by 2050 and coral reefs are perishing from exposure to increased oceanic heat, pollutants, and sedimentation (Anderson, et al., 2015). These coastline features once protected the shore from wave-action and saltwater inundation, but may not serve

those purposes in the future. Because heat is increasing at accelerated rates in high-altitude areas, trade wind inversions are occurring more often. As temperature and rainfall patterns are changing, endemic plants are being threatened (Krushelnysky et al., 2016). The loss of native species near high-altitude headwaters of rivers and streams will change watershed characteristics, allowing more non-native species to invade and further accelerating erosion rates.

The impacts of hydromodifications in Hawai'i will have severe potential consequences as climate changes. Wetlands protect from inland flooding, but also insulate the freshwater lens from rising sea levels which threaten to infiltrate Hawai'i's aquifers. Increased precipitation intensity will bring larger volumes of water into the state's streams, increasing flow speeds, impacting what remains of aquatic fauna, and ushering sediments and pollution into already struggling coastal environments. Researchers postulate that the very character of future flooding may evolve in the form of climate-driven flash flooding. This type of flooding is distinct in that it is not related to a swelling river overflowing its banks, but by heavy rainfall events causing sewer and drain infrastructure to become overwhelmed and fail (Joyce, 2016). Because traditional infrastructure was built based upon historic rainfall data, a changing climate poses serious threats to the ability of existing infrastructure to manage future rainfall events. Unfortunately, these events are already occurring in urbanized areas of the state, foreshadowing failures of another magnitude in the future.

As climate change brings more extreme and unpredictable storm events, homeowners and governments may not be able to keep up with the accelerating changes in their local environments. The Federal Emergency Management Agency (FEMA) flood

mapping, for example, accounts for 100 and 500-year storms, with 1% and 0.2% probabilities of annual occurrences, respectively. However, as probabilistic estimates of storm occurrences are outpaced and urbanization continues to claim natural floodplain areas, flood zones are changing more rapidly than FEMA flood maps can account for. Peak flows on O'ahu can range from hundreds to thousands of times greater than mean annual flow during flooding events (Oki, n.d.). Because homeowners are not required to purchase flood insurance if they are not in a FEMA designated flood zone, climate-induced flooding poses new financial risks.

### **A New Paradigm of Stormwater Management**

Green infrastructure provides a spectrum of customizable solutions with the potential to address the wide range of problems facing modern cities. Unlike the unhurried development of the world's forests and wetland systems, the term 'green infrastructure' is a recent addition to the lexicon of environmentalists and is still evolving. In its purest form, green infrastructure is nature; the term embodies the vast ecosystems of the world and the multitude of services they provide, including habitat, heat and flooding mitigation, clean air and water, and carbon sequestration. Green infrastructure was introduced through the work of Fredrick Law Olmstead, an influential 19<sup>th</sup> century landscape architect and scholar who associated green space with positive human health outcomes. Olmstead normalized the preservation of park space in high-value urban areas like Central Park in New York City, the United States Capitol Grounds in Washington D.C., and Olmsted Linear Park in Atlanta.

Green infrastructure is the meeting ground of the natural and built environments, and can be analyzed at several spatial scales. A narrow view of green infrastructure may relish the benefits of an individual park or project, while the broader regional<sup>5</sup> or even global view should present a wide-ranging, interconnected green system with incalculable benefits. In contemporary cities, green infrastructure has been utilized as a way to mimic natural processes that have been lost due to urbanization and development. In the United States, several cities have progressive outlooks on the implementation of green infrastructure, enacting policies to ensure it is considered as an alternative to grey infrastructure and providing incentives for its use. Philadelphia, New York City, New Orleans, and Seattle have led the way in promoting green infrastructure as a cost-effective, aesthetically pleasing, multi-benefit solution to urban issues. Green infrastructure offers additional co-benefits that traditional 'grey' infrastructure like pipes and conveyances cannot provide, including the provision of natural habitat areas, recreational spaces, environmental education, chemical-free water purification, property value improvements, reinvestment and revitalization, and opportunities to partner with and incentivize other beneficial projects, such as multi-modal paths and community parks.

One of the greatest issues facing modern cities, flooding, can be addressed through the implementation of green stormwater infrastructure (GSI) networks. GSI seeks to mimic the natural processes that have evolved to manage wet conditions. Cities around the nation have begun to combat combined sewer overflows with GSI, choosing to divert and treat water naturally and keep it away from the sewer system rather than upgrading aging grey infrastructure. Unlike grey infrastructure, once GSI is installed it can be adapted to suit changing conditions, further maximizing its cost-effectiveness. When used simultaneously, green



and grey infrastructure can complement one another by diverting runoff from sewer systems and reducing structural burdens, lowering conveyance and treatment costs, increasing failsafe capacity, adapting to climate variability, and allowing for smart urban growth.

In planning for Hawai'i's future, the effective management of stormwater is critical. Land-based nutrient pollution must be reduced, controlled, and contained in a more efficient manner; simultaneously increasing capacity as climate change brings unprecedented precipitation patterns. Runoff implications in Hawai'i are multi-faceted, resulting in coastal pollution and eutrophication, flooding, public health threats, economic stress, aesthetic issues, cultural devaluation of the landscape, and ecosystem degradation. Stormwater problems have also been amplified by historic alterations to the landscape, and will continue to evolve with the threats of climate change. The unique nature of Hawaiian stormwater runoff will require tailored solutions.

One of the greatest assets of GSI is its adaptability to different geographies, climates, and city sizes. GSI can be modified for wet or dry conditions, climate extremes, urban or rural settings, polluted areas, and spaces lacking recreation opportunities. As cities like Honolulu begin the implementation of GSI, they are looking to industry leaders for inspiration and guidance. However, solutions ideally suited in one location may be implemented in an area where their value is lost. In the state of Hawai'i, regional specificity is crucial to the maximization of stormwater benefits.

As the only state located in the tropics, solutions to Hawai'i's stormwater issues should be as distinct as the islands themselves. Appropriate GSI options should be selected on a site-specific level and case studies must be carefully scrutinized prior

to their application in new areas. Some GSI projects in Hawai'i have been careful to incorporate local materials, such as porous basalt rock, and cultural features, such as the wetland plant taro, into their designs. However, the application of GSI must be analyzed at local scale in order to promote success and customize co-benefits. The indiscriminate export of 'mainland' solutions, unsuited to the unique local conditions of the archipelago where they are placed, may not only lead to unsuccessful projects, but may discourage the application of GSI in the future.

Solutions tailored to consistent rainfall should be sited on windward sides of the islands, where as designs that can handle large, intermittent storms should be employed on the usually dry leeward sides. The placement of permeable pavement on the leeward side of an island, for instance, may be problematic due to the flashy nature of stormwater flow and sedimentation in these areas. The clogging of permeable materials could lead to excessive maintenance requirements. Similarly, the use of a rain garden design on the windward side of the island would likely have little value added, as windward areas allow limited percolation due to the already saturated nature of forest soils. Dry areas must carefully manage water resources and tend have high pollutant discharges with fast flows after periods of drought, making cisterns and cascading retention cells/terraced bioswales ideal matches to leeward conditions. Green roofs can suffer from both low and high moisture; they may require irrigation on leeward sides and adequate drainage on windward sides. Some solutions, such as tree planting, can be applied in any area. However, species must be carefully selected to promote successful growth and future recruitment. Prudent due diligence is necessary in the consideration of all GSI solutions in highly disparate local conditions.

Mainstream green infrastructure guidelines often provide case studies from the continental United States with disclaimers regarding local conditions. The *Greenworks for Climate Resilience* guidelines caution, “Coastal zones in the Pacific, Atlantic, Gulf of Mexico, and Great Lakes vary widely in climate, habitat types, and human impacts” (National Wildlife Federation, 2014). *Stormwater management in the Pacific and Caribbean Islands: A Practitioner’s Guide to Implementing Low Impact Development (LID)* associates vastly different island environments, with distinctive geologic and ecological conditions, with the same policy suggestions. The grouping of incompatible island environments, even those in the same geographic domain, can be problematic. Throughout the Pacific basin mangroves are prized as critical components of green infrastructure systems, however, in Hawai‘i mangroves are an exotic and highly invasive species. This incongruity makes an initiative to protect mangrove habitats on other islands vital, while the same efforts in Hawai‘i are potentially catastrophic.

Even ‘local’ green infrastructure guides consistently offer continental case studies and lack thoughtful adaptation for Hawaiian conditions. As a result, practitioners may struggle to differentiate solutions appropriate for varying climates, topographies, and levels of urbanization. Some Hawai‘i-specific guides are written by consulting firms from the continental United States, lacking an understanding of local conditions and consistently including case studies from incompatible habitat types and climate zones. *Low Impact Development: A Practitioners Guide* includes ‘island adaptations’ but still uses mainland conditions as foundational suggestions, even borrowing from the Georgia Stormwater Manual (Hawai‘i Office of Planning). The Hawai‘i guide uses figures from the Georgia manual, depicting residential and commercial site designs with limited applicability to Hawaiian

communities. One residential figure, for example, includes recommendations for design and drainage. Issues arise in consideration of the vast differences in ecology, climate, building norms, elevation, and neighborhood preferences between Hawai`i and Georgia. The Georgia Manual's "Better Site Design" suggestions include cul-de-sacs with bioretention, a traditional suburban amenity center, open vegetated channels, and no drainage system. While some of these suggestions may be implementable in certain parts of the islands, they are almost certainly incompatible to most areas, particularly neighborhoods situated on hillsides in leeward areas. Similarly, the "Better Site Design" for commercial spaces offered by the Georgia manual suggests detention ponds and large bio-retention areas, space-demanding solutions unlikely to be utilized in Hawai`i due to the state's high land values. Compounding these concerns are long-term maintenance and care commitments, which may be poorly understood if green infrastructure is implemented by out of state firms.

The use of green infrastructure is a best management practice in itself, however it has yet to be examined how green infrastructure can better meet location-specific needs in Hawai`i. In consideration of Hawai`i's highly variable and fitful precipitation patterns, projected shifts in rainfall due to climate change, unique microclimates, dramatic geography, and evolving land uses, local conditions must be thoughtfully incorporated into the selection of GSI options to ensure project aims are met. With the implementation of GSI in its infancy statewide, Hawai`i has the unique opportunity to build a foundation of thoughtful policy guidelines and provide selection assistance to maximize project effectiveness.

## Analysis and Methods

The following analysis will describe the goals of the study at large and define the experimental approach. A description of methods will delineate baseline assumptions used in the study and catalog the variables included in the analysis.

### Analysis

The judicious placement of GSI solutions is critical in establishing a framework for sustainable decision-making. The streamlining of the GSI selection and siting process will likely encourage the future use of sustainable solutions in island environments. In order to analyze which GSI solutions best suit local conditions in Hawai'i, a hypothetical exercise will illustrate a potential procedure for practitioners to follow when considering the use of green infrastructure. The island of O'ahu has been selected for this analysis because it is the most urbanized major Hawaiian island and has undergone the most environmental change spurred by human habitation. As the most populated island in the archipelago with almost one million inhabitants, O'ahu has the greatest potential impact for positive change in the alteration of its stormwater management regime.

Siting considerations include both qualitative and quantitative factors, which will then be incorporated into an ordinal combination suitability analysis. The siting suitability analysis will search for the best 'worst' areas to place GSI interventions. In



essence, siting will attempt to identify ecologically compromised areas in need of green infrastructure interventions. A second ordinal combination suitability analysis will be performed to analyze experimental site characteristics and further inform the GSI selection process. The spatial analysis outputs will serve as foundational information for the selection of GSI in consideration of local conditions on the island of O‘ahu.

Following this analysis, the results will be integrated with qualitative considerations. Peak stormwater runoff from each study area will be quantified to display hypothesized variations in stormwater management needs based upon differences in microclimates and local conditions at the site level. The synthesis of the suitability analysis and quantitative analysis will inform planning recommendations and policy suggestions.

## Methods

A two-step Ordinal Combination Suitability Analysis will be used to first identify experimental sites suitable for the placement of GSI, and then to further analyze local conditions governing the selection of effective GSI interventions at the site-specific scale. The Linear Combination method will not be utilized in order to avoid the potential biases associated with the assigning of variable weights.

Site selection will be informed by the identification of ecologically compromised areas in an Ordinal Combination Suitability Analysis. GSI intervention sites will be chosen where sub-optimal conditions impacting important natural resources are identified (i.e. poor terrestrial and near-shore water quality, high impervious surface cover and population density located near public beaches or coral reefs). Four experimental locations will be considered: two on the leeward and two on the windward sides. On each side of the island one site will be selected with a majority of impervious land cover, while the second site will be mostly pervious land cover. Variables considered in the site selection will include: geographic position, near-shore characteristics (such as the presence of public beach/coral reef and water quality ratings), terrestrial land use, percentage of impervious cover, and terrestrial water quality. After each experimental site is selected, the four sites will be analyzed to determine local conditions that may impact GSI efficacy. A second Ordinal Combination Suitability Analysis will be used to inform GSI selection. Variables considered in the suitability analysis will include slope, soil hydrology, floodplain coverage, and seasonal rainfall.

The range of validity for these findings will be limited to the Hawaiian archipelago, though the methods of this analysis may be applied in other island environments with local data and insights. This analysis is limited by the boundless variables that could potentially be considered, however the most seemingly influential factors were incorporated in an attempt to capture the most realistic local outcomes. Standards associated with each variable are discussed below.

## Assumptions and Metrics

Knowledge of industry ‘best practices’ for each GSI solution are necessary to implement successful projects at the local level. Construction specifications, specifically slope, will be used to standardize the analysis. The GSI solutions below are structural solutions with the potential to capture, infiltrate, and treat stormwater on minimally sloped land (US EPA).

### ***GSI and Corresponding Slope Requirements***

<i>GSI Practice</i>	<i>Maximum Slope</i>	<i>Additional Considerations</i>
Bioretention/Vegetated Swale/Planter Box	6%	Stepped Pools/Weirs can slow flows. Minimum slope 1%. Minimum separation distance of 3’ to high water table.
Dry Well	6%	
Diversion/Infiltration Berm (Terracing)	25%	Not to be used with shallow soils near bedrock or in landslide-prone areas.
Infiltration Trench	5%	May be stepped down a slope.
Permeable Asphalt	5%	Substorage baffles may increase storage volume. Should not be placed above compacted fill soils. Not to be used in high pollutant loading sites.

Some GSI solutions, like tree planting, green roofs, and water harvesting, are viable in both leeward and windward locations and are not ground slope-limited. Therefore, these solutions were not considered in this suitability analysis. Despite their viability, these solutions still have special considerations. Trees must be sited according to their ideal habitat type and space needs. Cisterns are prone to algal growth if placed in warm and sunny locations and do not remove pollutants. Green roofs may require irrigation in

dry areas or proper drainage in wet areas and must have a roof slope of 20% or less. Other solutions not considered include wetland creation and stormwater ponds, both of which require large, flat land areas not likely available or financially feasible in most regions of Hawai'i.

## Results

### Selection of Potential Sites for Study

Experimental sites were selected based on the evaluation of sub-optimal conditions impacting important natural resources. The presence of poor terrestrial and near-shore water quality, impervious surface cover, and proximity to coral reefs determined locations that were good candidates for GSI interventions. Following this analysis, the candidate areas were evaluated for physical site suitability. This analysis was based on slope, flooding vulnerability, and proximity to streams or stormwater outlets.

The following characteristics were ultimately included in the consideration of each experimental site selected:

- Slope  $\leq 5\%$
- In Special Flood Hazard Area (SHFA) [A, AE, AO, V, or VE]
- Within 500 ft. of stream or stormwater outflow to ocean
- Coral reef present offshore within 2000 feet

- Impervious surface present
- Inland/Terrestrial Water Quality Good (vs. Great)
- Near shore Water Quality A (vs. AA),

## Slope

Slope was calculated in degrees using a raster digital elevation model (DEM) of O'ahu. These delineations were converted by identifying the degree of slope and converting it into the percent slope, ( $\% \text{ slope} = 100 * (\text{rise/run})$  or  $\text{Degrees} = \tan^{-1}(\text{Slope Percent}/100)$ ). Slope was classified according to studies of GSI effectiveness, ( $\leq 5\%$ ) ( $\leq 6\%$ ) ( $\leq 25\%$ ) ( $\leq 75\%$ ) ( $\leq 90\%$ ). These slope percentages were used as break values to identify viable GSI sites. Sites with ( $\leq 5\%$ ), ( $\leq 6\%$ ), or ( $\leq 25\%$ ) may be candidates for GSI interventions, while sites with ( $\leq 25\%$ ) slope are not appropriate.

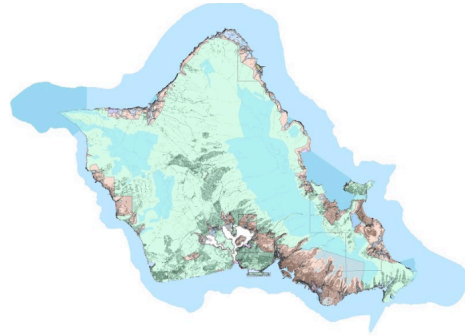
### ***Slope Conversion:***

5% slope= 2.86 degrees  
 6% slope=3.43 degrees  
 25% slope= 14.04 degrees  
 50% slope=26.57 degrees  
 100% slope= 45 degrees  
 'Infinite' slope= 90 degrees

### ***Boolean Reclassification:***

Slope 5% or less=1, All else=0  
 Coral Reef Present=1, All else=0  
 Nearshore WQ= A=1 AA=0  
 Terrestrial Water Quality= Ok=1 Good=0  
 Streams (buffer) [500 feet]=1 Further=0  
 Coral Reef (buffer) [2000 feet]=1 Further=0  
 Land cover: Impervious Surface= 1 Undeveloped=0

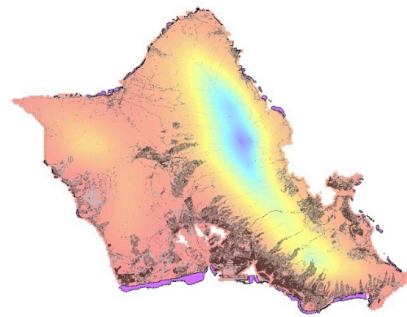




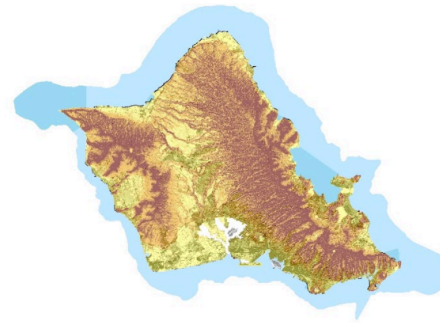
SFHA's, Near Shore Water Quality



Streams, Terrestrial and Near Shore Water Quality



Annual Rainfall, Coral Reef Locations



Slope, Impervious Surfaces, Near Shore Water Quality

## **Finding Peak Discharge**

### *Rainfall Calculations:*

Four study sites were chosen from the results of the suitability analysis. Two sites were chosen on each side of the island, with one site demonstrating the effects of mostly pervious land cover and the other representative of a majority of impervious land cover. The pervious sites consisted of open public park space, while the impervious sites were predominantly covered by asphalt parking areas. Though the study sites were situated on opposite sides of the island, two on the windward side and two on the leeward side, both the pervious and impervious sites met the established criteria of the ordinal combination suitability analyses and are utilized in very similar ways. These sites were selected in order to make conjectures and comparisons as equal as possible.

## Windward Study Sites





## Leeward Study Sites



As a foundational comparison of rainfall conditions, National Oceanic and Atmospheric Association (NOAA) data was used to gauge local rainfall intensity in the immediate areas of the study sites. NOAA data for two rain gauge stations, the Honolulu International Airport on the leeward side of O‘ahu, and Kailua Fire Station on the windward side of O‘ahu, were used to explore average rainfall intensity metrics for a 25 year, 60-minute storm. (NOAA, n.d.).

***NOAA Rain Gauge Stations***

<i>Location</i>	<i>Year-Storm</i>	<i>Inches/Hour</i>
Honolulu International Airport Elevation: 7 feet	25	2.65
Kailua Fire Station Elevation: 10 feet	25	3.32

The Rational Method was utilized to estimate peak runoff for the four study sites. The Rational Method was derived in 1889, but remains appropriate for use on small sites with minimal storage. The City and County of Honolulu includes the Rational Method in its handbook ‘Rules Relating to Storm Drainage Standards’ (City and County of Honolulu, 2000).

The Rational Method Equation,  $Q=CiA$ , Where:

Q= Peak Rate of Runoff [cubic feet/second]

C= Runoff Coefficient [dimensionless, 0=perfectly pervious 100=perfectly impervious]

i= Average intensity of rainfall for the time of concentration ( $T_c$  (minutes)) for a selected design storm (25-year storm) [inches/hour]

A= Drainage Area [acres]



### **Runoff Coefficient (C)**

Runoff coefficients were derived from the 'Storm Water Permanent Best Management Practices Manual' (State of Hawai'i Department of Transportation Highways Division, 2007). Land use classifications derived from GIS were incorporated into the calculations by multiplying the percentage of each land use by its assigned runoff coefficient. This process was repeated for each land use type found on the study site. Finally, the products were summed to find the total runoff coefficient for each site.

The classifications and their coefficients included: Evergreen (0.2), Bare Land (0.45), Impervious (0.93), Open Space Developed (Leeward: 0.3, Windward: 0.45), Scrub/Shrub (0.3), and Unconsolidated Shore (0.2). All rankings were the same in the leeward and windward calculations, with the exception of Open Space Developed. From satellite imagery it is clear that the leeward pervious site is mostly bare dirt, while the windward pervious site is predominantly grassy turf. As such, the sides of the island were assigned different runoff coefficients.

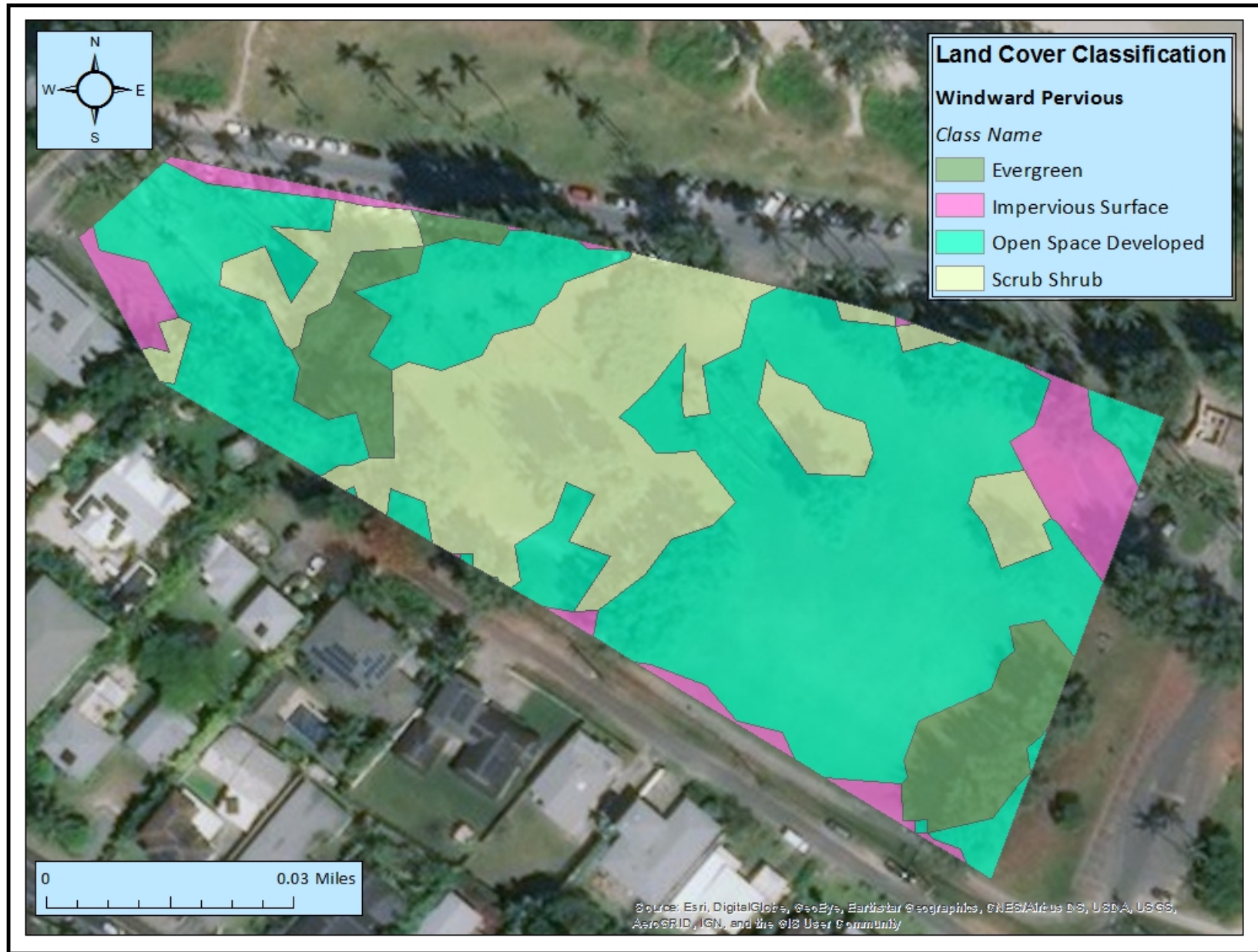
***Land Use Classifications Areas (m<sup>2</sup>)***

<i>Site</i>	<i>Bare Land</i>	<i>% of Total</i>	<i>Evergreen</i>	<i>% of Total</i>	<i>Impervious Surface</i>	<i>% of Total</i>	<i>Open Space Developed</i>	<i>% of Total</i>
Windward Pervious	-	-	1309.47	9.26%	981.73	6.94%	7948.8	56.21%
Windward Impervious	-	-	1172.36	13.05%	4794.18	53.36%	2199.88	24.48%
Leeward Pervious	0.1	0.00%	3728.37	17.14%	1676.55	7.71%	15766.42	72.46%
Leeward Impervious	0.45	0.00%	1286.78	8.36%	11356.23	73.82%	2198.98	14.29%

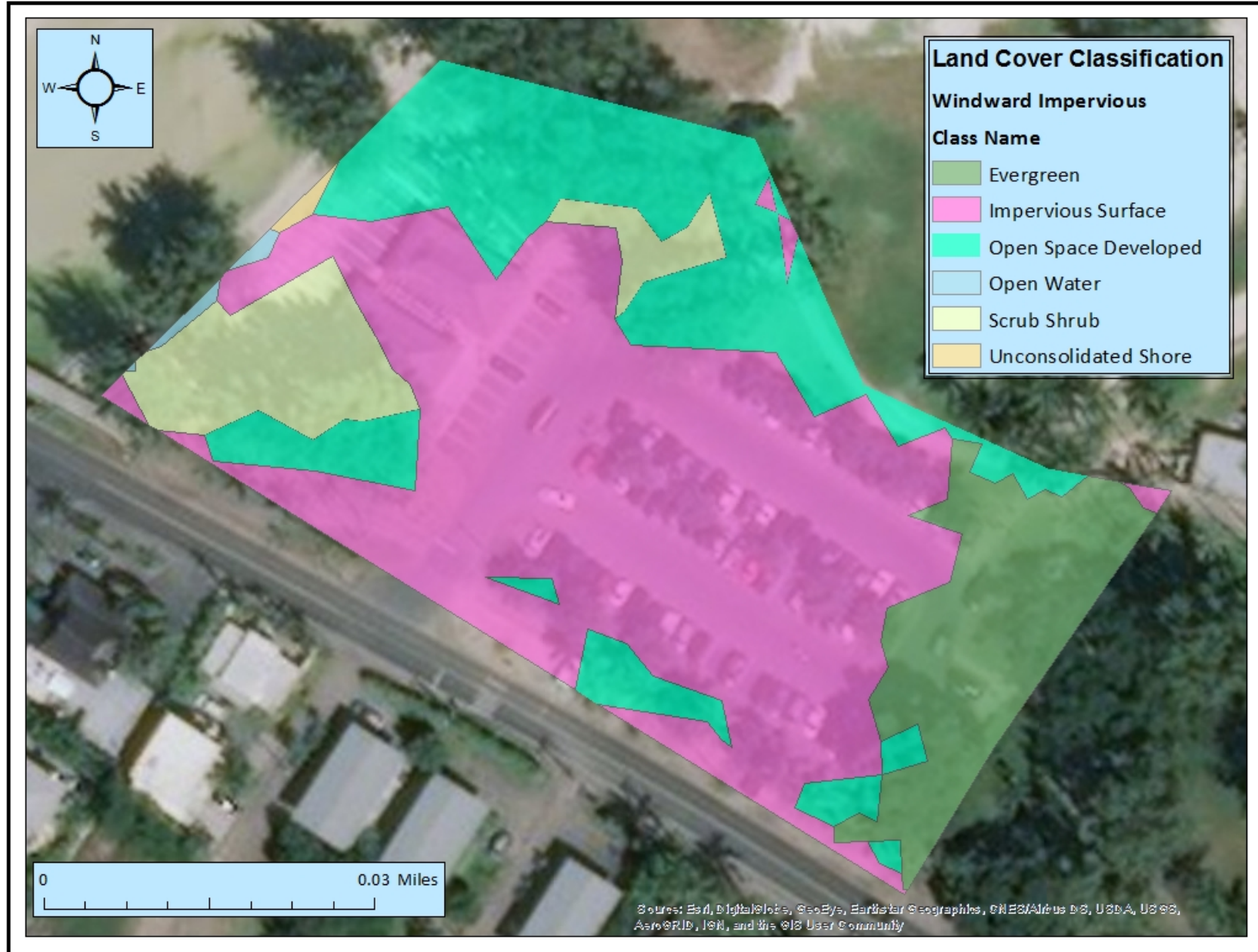
***Land Use Classifications Areas (m<sup>2</sup>) Cont.***

<i>Site</i>	<i>Unconsolidated Shoreline</i>	<i>% of Total</i>	<i>Scrub/Shrub</i>	<i>% of Total</i>	<i>Total</i>	<i>Runoff Coefficient</i>
Windward Pervious	-	-	3901.5	27.59%	14141.5	0.33
Windward Impervious	-	-	818.63	9.11%	8985.05	0.66
Leeward Pervious	22.97	0.11%	562.9	2.59%	21757.31	0.33
Leeward Impervious	-	-	541.21	3.52%	15383.65	0.79

## Windward Pervious Study Site, Kailua Beach Park

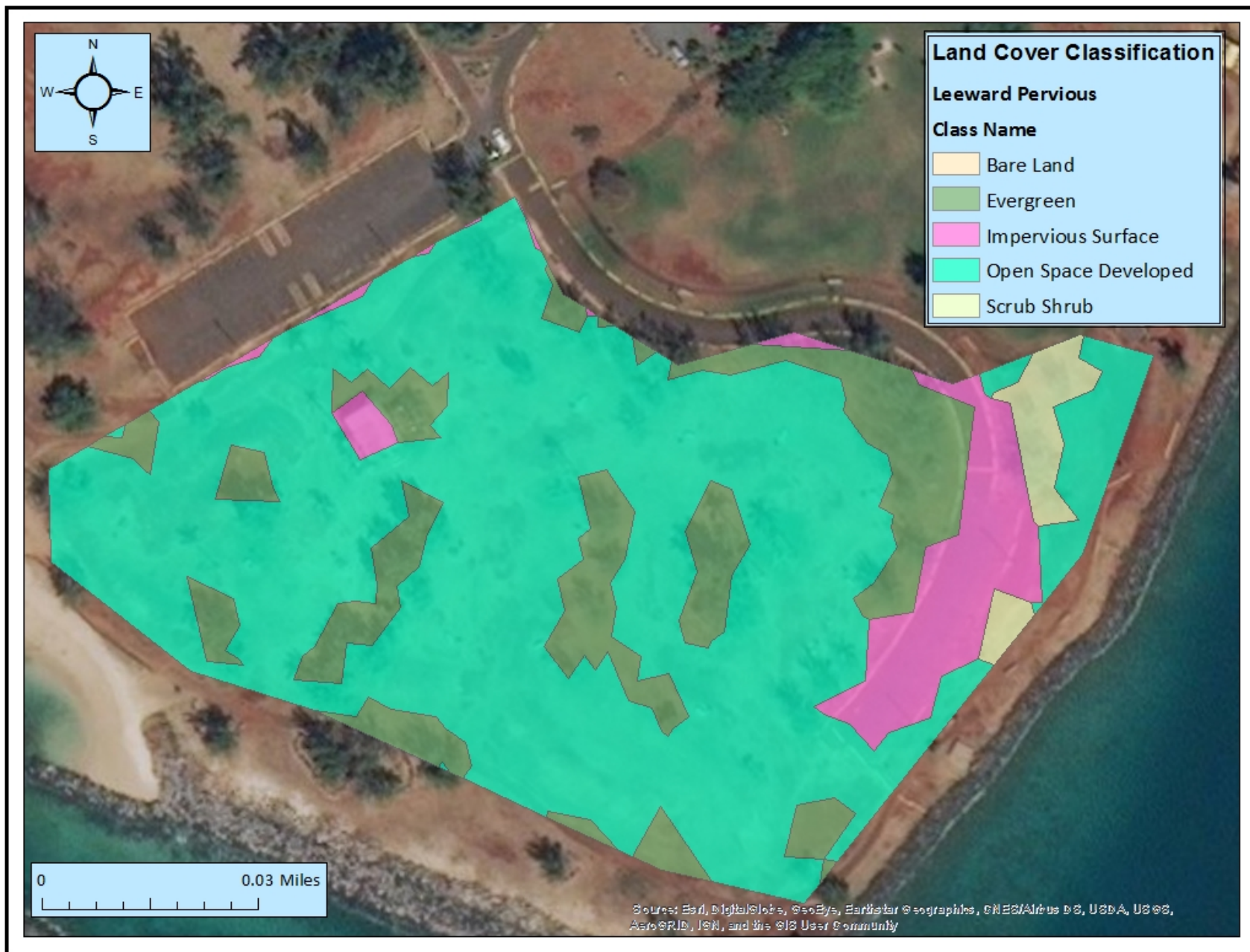


## Windward Impervious Study Site, Kailua Beach Park Parking Lot

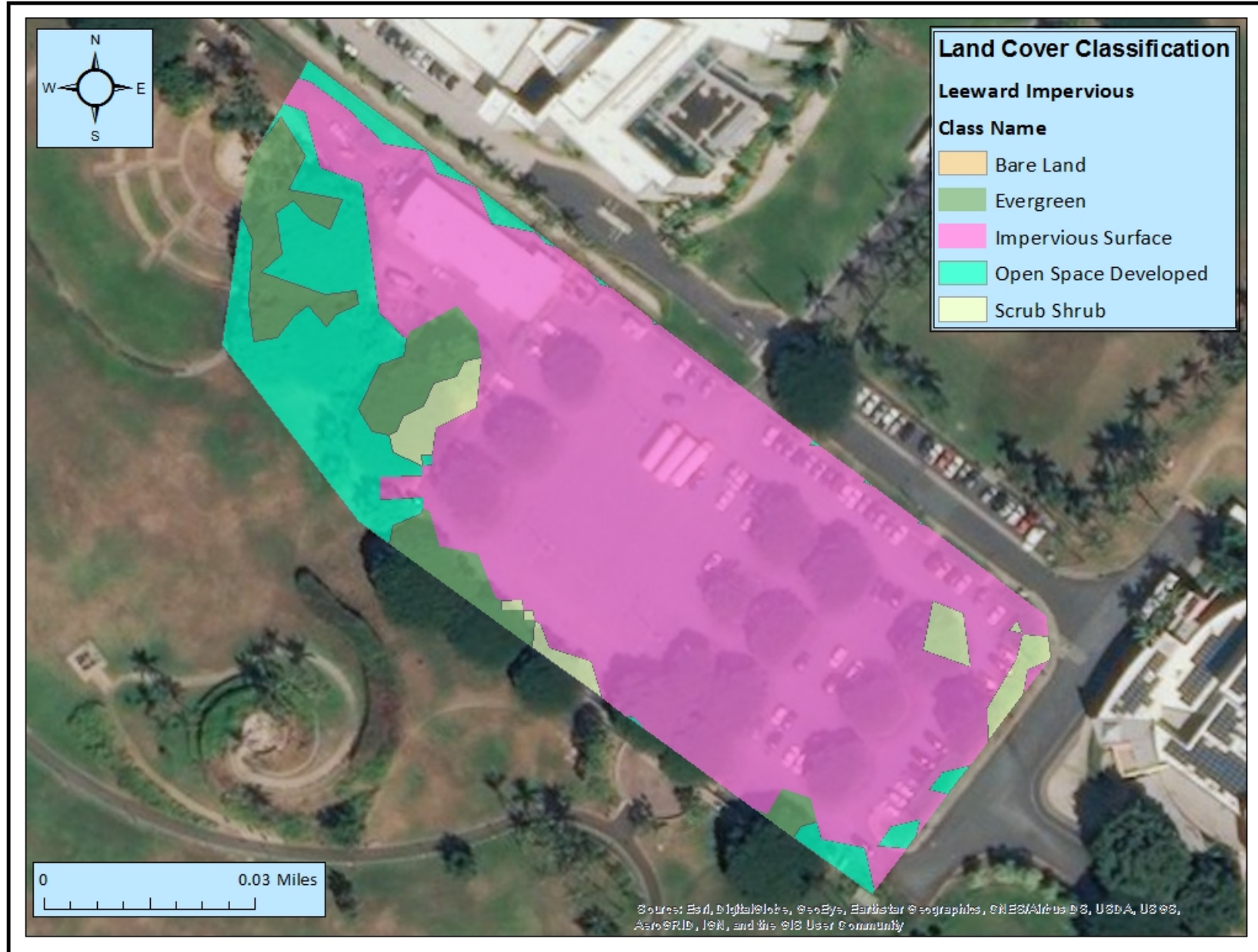




# Leeward Pervious Study Site, Sand Island State Recreation Area



## Leeward Impervious Study Site, Kaka'ako Waterfront Park Parking Lot



### Time of Concentration ( $T_c$ )

Time of Concentration was derived from the USDA guide, 'Urban Hydrology for Small Watersheds (TR-55)'. (USDA NRCS, 1986). Time of Concentration ( $T_c$ ) denotes the amount of time it takes a single drop of stormwater water to travel from the most remote point in a subcatchment to the catchment's outlet, the point of water collection. The calculation of the variable  $T_c$  is necessary to determine each site's peak discharge using the Rational Method. Once  $T_c$  is determined, it is used to estimate the Rational Method value 'i' from a frequency-duration-intensity table for a storm duration equal to  $T_c$ .

Infiltration-based GSI techniques require an understanding of soil limitations at the site level. The saturated hydrologic conductivity ( $K_{sat}$ ) provides a measure of soil permeability based upon soil type.  $K_{sat}$  classes are especially helpful in complex ecosystems like those seen in Hawai'i, where up to ten soil types are present.  $K_{sat}$  classifications describe soil permeability speeds.

In order to determine Time of Concentration ( $T_c$ ) the watershed lag method is used (USDA NRCS, 2010).

$$T_c = I^{0.8} + (S+1)^{0.7} / 1,140 Y^{0.5}$$

Where:

$T_c$  = Time of Concentration, h

$I$  = Flow Length, ft

$Y$  = Average Watershed Land Slope, %

$S$  = Maximum Potential Retention, in  
 $= (1,000/cn') - 10$

○  $cn'$  = The Retardance Factor (Approximated by CN)



The Ksat is used to determine  $cn'$ , the retardance factor, approximated as the curve number (CN). CN can range between 30 and 100. Low values represent higher permeability, with high values indicating high runoff potential. CN is derived through an investigation of soil types, which have been categorized by the NRCS into four hydrologic soil groups (HSGs). On the windward side of the island, both test plots fall in hydrologic soil group A. Group A soils have a high infiltration rate, which corresponds to low runoff potential and are often composed of deep, well-drained sand and gravel which easily transmit water. On the leeward side of the island, both test plots fall in hydrologic soil group B. Group B soils are characterized by languid infiltration rates. They are mainly deep and moderately drained. These soils range texturally from moderately fine to coarse and have a modest rate of water transmission (USDA NRCS, 2007).

On the windward side, hydrologic group A soils in the largely impervious site are assigned a CN of 98, while the vegetated (>75% grass cover) pervious site is assigned a CN of 39. On the leeward side, hydrologic group B soils in the impervious site are assigned a CN of 98, while the mostly barren pervious site (<50% grass cover) is assigned a CN of 79 (USDA NRCS, 1986).

### Maximum Potential Retention (S)

<i>Site</i>	<i>Cn' (approximated as CN)</i>	<i>S= (1,000/cn')-10</i>	<i>Computed S Value</i>
Windward Pervious	39	$S = (1,000/39) - 10$	15.64
Windward Impervious	98	$S = (1,000/98) - 10$	0.20
Leeward Pervious	79	$S = (1,000/79) - 10$	2.66
Leeward Impervious	98	$S = (1,000/98) - 10$	0.20

Slope is about 5% for each of the four test sites. Flow length, *l*, was computed using the longest likely flow length across the site by measuring the widest point of each site. Drainage areas for each site were calculated using ESRI ArcMap 10.3.

### Flow length (l)

Site	Flow length (m)	Flow length (ft)
Windward Pervious	96.6	316.93
Windward Impervious	145.2	476.38
Leeward Pervious	82.4	270.34
Leeward Impervious	76.9	252.30

### T<sub>c</sub>, Time of Concentration + i, Intensity

Site	Variables	Formula	T <sub>c</sub>	T <sub>c</sub> (Minutes)	Precipitation Intensity, 25 Year Storm* (Inches/Hour)
Windward Pervious	CN= 39 l= 316.93 ft S= 15.64 Y= 5%	$T_c = [316.93^{0.8} * (15.64 + 1)^{0.7}] / [1,140 * 5^{0.5}]$	0.28	16.8	7.18
Windward Impervious	CN= 98 l= 476.38 ft S= 0.20 Y= 5%	$T_c = [476.38^{0.8} * (0.20 + 1)^{0.7}] / [1,140 * 5^{0.5}]$	0.06	3.6	11.6
Leeward Pervious	CN= 79 l= 270.34 ft S= 2.66 Y= 5%	$T_c = [270.34^{0.8} * (2.66 + 1)^{0.7}] / [1,140 * 5^{0.5}]$	0.09	5.4	9.28
Leeward Impervious	CN= 98 l= 252.30 ft S= 0.20 Y= 5%	$T_c = [252.30^{0.8} * (0.20 + 1)^{0.7}] / [1,140 * 5^{0.5}]$	0.04	2.4	9.28

\*Precipitation Intensity Derived from NOAA's National Weather Service Hydrometeorological Design Studies Center Precipitation Frequency Data Server (PFDS) - Windward Sites Station: Kailua Fire Station, Leeward Sites Station: Honolulu International Airport

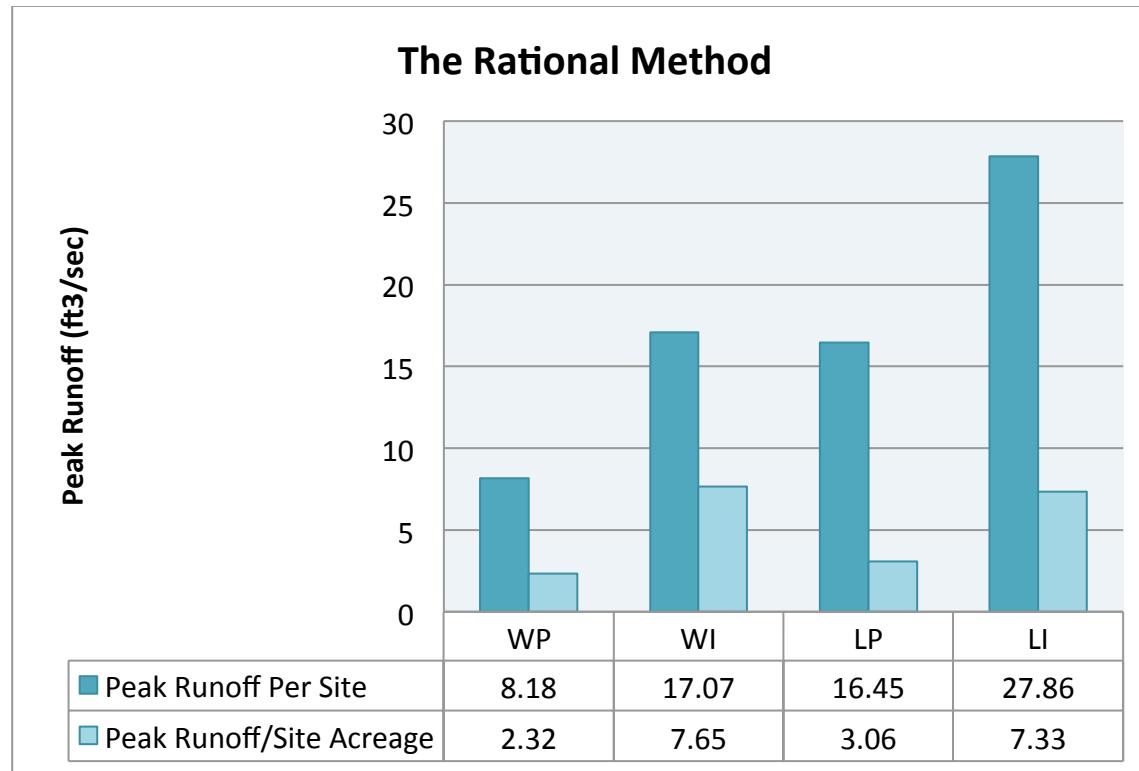
### Synthesizing the Components for the Rational Method Equation

After deriving each of the variables for the final equation, peak discharge (Q) was calculated using the Rational Method. Q represents peak surface runoff rate in cubic feet per second.

#### *Study Site Peak Runoff (ft<sup>3</sup>/sec) Present Condition*

<i>Windward Site Peak Runoff (ft<sup>3</sup>/sec)</i>	<i>Windward Site Peak Runoff Adjusted Per Acre (Q/Acre)= ft<sup>3</sup>/sec per Acre</i>	<i>Leeward Site Peak Runoff (ft<sup>3</sup>/sec)</i>	<i>Leeward Site Peak Runoff Adjusted Per Acre (Acres/Q)= ft<sup>3</sup>/sec per Acre</i>
Pervious (WP)- Q= (0.33)(7.18)(3.49) Q= 8.18	Pervious (WP)- 8.18/3.49 2.32	Pervious (LP)- Q= (0.33)(9.28)(5.37) Q=16.45	Pervious (LP)- 16.45/5.37 3.06
Impervious (WI)- Q= (0.66)(11.6)(2.23) Q=17.07	Impervious (WI)- 17.07/2.23 7.65	Impervious (LI)- Q= (0.79)(9.28)(3.80) Q=27.86	Impervious (LI)- 27.86/3.80 7.33

### Current Conditions Results



In order to demonstrate the potential impact of GSI on site-specific stormwater modeling, the percentage of impervious surface on each site was reduced and replaced with green infrastructure area. The percentage of impervious surface on the pervious sites was completely removed, a 7% reduction on the windward pervious and 8% reduction on the leeward pervious site. The

percentage of impervious surface was reduced by 20% on each of the impervious sites. The value of 20% was chosen to incorporate bioswales without an unrealistic reduction of parking lot functionality due to a drastic decrease in space numbers.

As a result of these hypothetical changes in land use, water will interact with the sites differently. In order to conceptualize this change, the runoff coefficients for each study site were recalculated, taking into account the reduction in impervious surface and addition of pervious surface. The areas of impervious surface that are proposed to change from asphalt to GSI were changed from a 0.93 runoff coefficient to a 0.2 runoff coefficient to represent gains in perviousness through the introduction of bioswales. The experiment is repeated with the 100% removal of asphalt and replacement with permeable surface material, a process which would not displace any parking spots. Permeable asphalt has a runoff coefficient between 0.25 and 0.35 (Massachusetts Low Impact Development Toolkit 2014). The coefficient of 0.30 was used to moderate this range. This experimental modeling process can be repeated with any GSI type as long as a runoff coefficient for the new land use is derived.

***Study Site Runoff Coefficients Under Present and Experimental Conditions***

<i>Study Site</i>	<i>Runoff Coefficient with Present Conditions</i>	<i>Runoff Coefficient with Bioswales</i>	<i>Runoff Coefficient with Permeable Asphalt</i>
Windward Pervious	0.33	0.28	0.29
Windward Impervious	0.66	0.51	0.32
Leeward Pervious	0.33	0.28	0.28
Leeward Impervious	0.79	0.63	0.31

***Proposed GSI Interventions in Acres***

<i>Site Name</i>	<i>Site Acreage</i>	<i>Impervious Acreage, Present Conditions</i>	<i>Impervious Acreage with Bioswales, Proposed</i>	<i>Bioswale Acreage, Proposed</i>	<i>'First Flush' Stormwater Intercepted by Bioswales* (Gallons)</i>	<i>Impervious Acreage with Permeable Asphalt, Proposed</i>	<i>Permeable Asphalt Acreage, Proposed</i>	<i>'First Flush' Stormwater Intercepted by Permeable Asphalt * (Gallons)</i>
Windward Pervious	3.49	0.24	0	0.24	6,516.96	0	0.24	6,516.96
Windward Impervious	2.23	1.18	0.82	0.24	6,516.96	0	1.18	32,041.72
Leeward Pervious	5.37	0.41	0	0.41	11,133.14	0	0.41	11,133.14
Leeward Impervious	3.80	2.81	2.25	0.56	15,206.24	0	2.81	73,302.74

\*'First Flush' refers to the first inch of rainfall on a site. One inch of rain falling on 1 acre of ground is equal to about 27,154 gallons (USGS).

By substituting these values into the Rational Method Equation, we can estimate the change in peak runoff per site and per acre. With modest adjustments to impervious surface coverage, each site experiences a reduction in peak runoff by promoting rainfall infiltration.



**Study Sites Modeled with Bioswales**

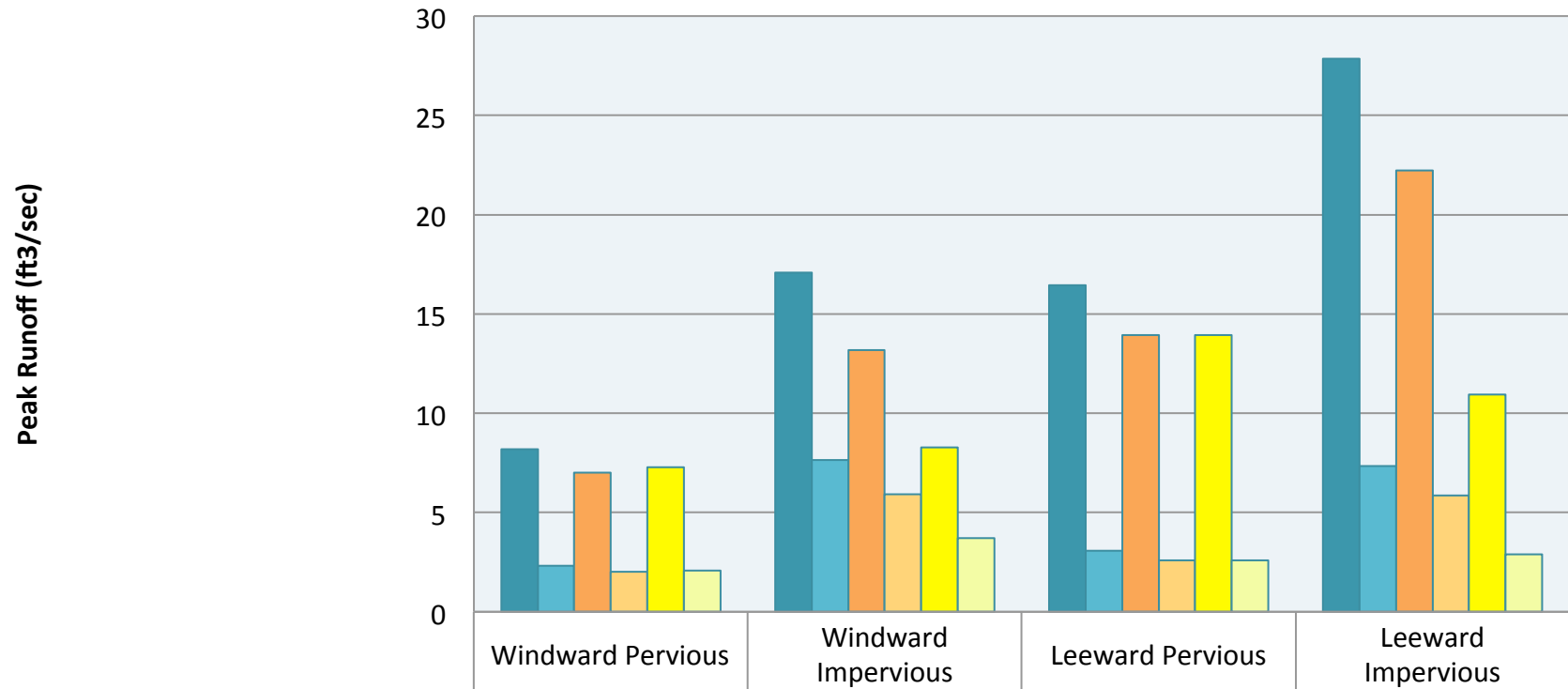
<i>Windward Site Peak Runoff (ft<sup>3</sup>/sec)</i>	<i>Windward Site Peak Runoff Adjusted Per Acre (Q/Acre)= ft<sup>3</sup>/sec per Acre</i>	<i>Leeward Site Peak Runoff (ft<sup>3</sup>/sec)</i>	<i>Leeward Site Peak Runoff Adjusted Per Acre (Acres/Q)= ft<sup>3</sup>/sec per Acre</i>
Pervious (WP)- Q= (0.28)(7.18)(3.49) Q= 7.02	Pervious (WP)- 7.02/3.49 2.01	Pervious (LP)- Q= (0.28)(9.28)(5.37) Q=13.95	Pervious (LP)- 13.95/5.37 2.60
Impervious (WI)- Q= (0.51)(11.6)(2.23) Q=13.19	Impervious (WI)- 13.19/2.23 5.91	Impervious (LI)- Q= (0.63)(9.28)(3.80) Q=22.22	Impervious (LI)- 22.22/3.80 5.85

**Study Sites Modeled with Permeable Asphalt**

<i>Windward Site Peak Runoff (ft<sup>3</sup>/sec)</i>	<i>Windward Site Peak Runoff Adjusted Per Acre (Q/Acre)= ft<sup>3</sup>/sec per Acre</i>	<i>Leeward Site Peak Runoff (ft<sup>3</sup>/sec)</i>	<i>Leeward Site Peak Runoff Adjusted Per Acre (Acres/Q)= ft<sup>3</sup>/sec per Acre</i>
Pervious (WP)- Q= (0.29)(7.18)(3.49) Q= 7.27	Pervious (WP)- 7.27/3.49 2.08	Pervious (LP)- Q= (0.28)(9.28)(5.37) Q=13.95	Pervious (LP)- 13.95/5.37 2.60
Impervious (WI)- Q= (0.32)(11.6)(2.23) Q=8.28	Impervious (WI)- 8.28/2.23 3.71	Impervious (LI)- Q= (0.31)(9.28)(3.80) Q=10.93	Impervious (LI)- 10.93/3.80 2.88

## Experimental Results

### The Rational Method



■ Present Conditions	8.18	17.07	16.45	27.86
■ Present Conditions Per Acre	2.32	7.65	3.06	7.33
■ With Bioswales	7.02	13.19	13.95	22.22
■ With Bioswales Per Acre	2.01	5.91	2.60	5.85
■ With Permeable Asphalt	7.27	8.28	13.95	10.93
■ With Permeable Asphalt Per Acre	2.08	3.71	2.60	2.88

## Interpreting the Results

As seen in the graph of experimental results above, GSI interventions perform in different ways on each site. The experimental replacement of conventional asphalt with its pervious alternative outperformed the use of bioswales in peak flow reduction and in the maintenance of all existing parking spaces. However, pervious asphalt would not provide any aesthetic improvement to the area or filter pollutants from stormwater as bioswales could. Despite making adjustments to improve translatability, the site results are not directly comparable. The pervious sites had small areas of existing impervious land cover (7% and 8% as compared to 20% reductions on each of the impervious study sites), which reduced the impact that the complete removal of impervious surfaces would have on the final results. Because of this, the reduction of impervious surfaces had less of an effect on the pervious sites than the impervious sites.

Interestingly, though the windward study sites receive far more rainfall on an annual basis than the leeward sites, local leeward conditions like reduced soil permeability and vegetative cover make GSI solutions on the leeward side of O'ahu more impactful. As climate change is anticipated to bring greater rain volumes to the leeward side of O'ahu, these results deserve particular attention. As previously mentioned, leeward sites may be prone to sedimentation due to the intermittent strong storms that are typical of the region. As a result, the long-term maintenance requirements of solutions like pervious asphalt must be considered during GSI evaluation.

## Policy Recommendations

This analysis reinforces that site conditions including land use, terrain, and regional microclimates should inform GSI selection. Currently, there is no indication of the importance of analyzing local conditions on a site before proceeding with project implementation. Hawai'i's minimal selection of green infrastructure and low impact development guides provide basic suggestions based on slope and soil conditions, but do not integrate the other factors upon which a GSI project's success or failure may hinge. The state of Hawai'i has no ordinances, policies, subsidies, or incentives pertaining to the use of GSI. As a point of clarification, Hawai'i has a Green Infrastructure Authority (HGIA), but its focus is on providing loans for renewable energy. In order to promote the use of GSI throughout the Hawaiian Islands, state and local officials should consider the development of guiding policies and clear procedures for site analysis. As long as GSI remains pure suggestion, developers will lack a compelling interest in changing their operating strategies. Passive spaces, such as the public parks and parking lot sites considered in this analysis, are potential starting points for the incorporation of GSI through site retrofits.

Because Hawai'i has no existing legislation to encourage the use of GSI, the state may consider using an existing policy as a model. In Atlanta, Georgia, the use of green infrastructure is promoted through the passage of the Post-Development Stormwater Management Ordinance, which requires GSI on new projects and redevelopment efforts. Like Honolulu, Atlanta has suffered from chronic combined sewer overflows, disproportionately impacting real estate values and threatening health in low-income areas. In

Atlanta, applicable developments are required to capture, infiltrate, evapotranspire, or reuse the ‘first flush’, or the first inch, of stormwater that falls on a site for up to a 100-year storm (Atlanta Watershed, 2013). The city of Seattle has set a goal of managing 700 million gallons of stormwater with GSI by 2025 (Sustainable Cities Institute, 2013). Combined sewer overflows plague Kansas City, which is working to replace sewer pipes from the late 17<sup>th</sup> Century. The city has committed over \$2 billion towards a 25-year Overflow Control Program, which combines GSI pilot projects and grey infrastructure improvements. Philadelphia, New York, and Chicago are also leading the way in the implementation of GSI through executive orders and consent decrees.

None of these model cities can fully meet the comprehensive needs of GSI implementation in Hawai‘i because they do not share the island’s unique orographic precipitation patterns or sensitive near-shore coastal resources. Even more critically, O‘ahu is already highly developed, making new development ordinances like Atlanta’s post-construction stormwater ordinance a largely ineffective tactic. Localities may consider such legislation if they anticipate major redevelopment or urban expansion in the future. Instead, officials may consider the use of an incentive-based tool. Incentive-based tools may involve subsidies for the construction of GSI and subsequent stormwater fee reductions for the maintenance of stormwater interventions onsite. However, a major barrier to such a policy in Honolulu is the city and county’s lack of established stormwater utilities or fee systems. Recently passed House Bill 1325 allows the cities and counties of Hawai‘i to institute stormwater user fees, however none have been initiated since the bill’s passage. Should such a utility be established, property owners may pay a fee based upon their lot’s impervious surface cover. These monthly fees could be used to create city and countywide GSI projects in problem areas, such as the vast impervious parking lots

surrounding critical coral reef and beach areas in the leeward port of Honolulu. Stormwater fees would be waived for property owners who reduce impervious surface coverage below an established threshold or install GSI interventions onsite. Additionally, the local government may consider mandatory GSI retrofits for chronic combined sewer overflow zones, coastal property owners, and industrial polluters.

A model program could be based upon the city of Minneapolis, Minnesota, which has instituted a similar incentive-based program to promote the use of alternative stormwater management. Beginning in 2005, Minneapolis began to assess stormwater utility fees as an additional line item on property owner's utility bills. Fees that were previously imbedded within sewer charges became a more transparent municipal cost to both the utility and the customers they served. The city provides two options to reduce these fees, both of which involve the use of on-site constructed stormwater quantity management tools, best management practices in stormwater control. In Minneapolis, stormwater fees are halved if the site can manage a 10-year, 24-hour storm. If a site can manage a 100-year, 24-hour storm, the whole stormwater fee is credited. Additional reductions are available for stormwater quality improvements (City of Minneapolis). Homeowner consultations and guidance for the installation of these tools, such as the streamlined recommendations of a local site analysis, could assist with the customization of GSI at the site-specific scale.

## Concluding Thoughts

Rainfall disparities in orographically influenced areas provide opportunities for the tailoring of GSI options. By mapping individual sites in distinct microclimates, analysts can better display differences in local needs and conditions. Even sites in the same microclimate with different land cover conditions (i.e. pervious v. impervious) have different responses in a rainstorm, despite having the same slope, soil conditions, and virtually the same location within the microclimate zone. By differentiating site conditions through mapping and quantitative analysis, we can more clearly understand the need for distinct stormwater management solutions at the site-specific level.

The choice of GSI does not only depend on the rate of runoff on a site, it also can vary depending on the needs and desires of the local community. Like costs, time, maintenance requirements, and community buy-in, the co-benefits of GSI are important considerations in the planning process. Co-benefits like aesthetic beauty, recreational space, harvested water for gardening, and habitat creation are great ways to encourage the use of GSI over conventional stormwater management solutions, which do not offer any supplementary amenities.

However, if a project is sold on the gamut of co-benefits it will provide to the community and it fails to deliver on the promise of these benefits, the community may be discouraged from using GSI in the future. The success of each GSI project is crucial because it is the potential inspiration for the next one. If a project fails, the implications of the single project's failure are greater than the

sum of its parts. Over time, a network of GSI constructed throughout a community will better serve its overall needs by more accurately ‘recreating’ the natural ecosystem services that would have been provided by the environment prior to development. A project’s failure means not only the absence of its promised co-benefits, but also reduced incentives for future GSI projects and the diminishing network of ecosystem service replication across a community as a whole.

GSI faces inherent challenges in its widespread application. In an industry that prides itself on exactness, environmental engineers can be wary of trial-and-error. However, the increasing unreliability of historic climate data in the face of future climate projections may represent a sea change in the most basic stormwater management assumptions. The use of GSI offers a more flexible and adaptable approach to stormwater management in an uncertain future, as compared to rigid and permanent grey infrastructure. The experimental nature of GSI can be tempered by the use of procedures such as those presented in this analysis.

The incorporation of microclimates, as well as climate change projections, into stormwater design will make interventions more effective at the site, regional, and inter-island scales. By isolating the design components that can impact GSI performance and using these factors to analyze ideal siting and placement, GSI solutions achieve a greater level of technical analysis and have higher potential to achieve success. In the short-term, successful projects will improve the daily lives of local communities impacted by localized flooding and stormwater pollution. In the long-term, GSI efficacy fosters the widespread utilization of alternative stormwater management, promotion of environmental education, and restoration of natural ecosystem functions at a broad scale.



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### ***GIS Data Sources:***

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National Land Cover Database. [https://www.mrlc.gov/nlcd01\\_data.php](https://www.mrlc.gov/nlcd01_data.php)  
State of Hawaii Office of Planning. <http://planning.hawaii.gov/gis/download-gis-data/>

### ***Pictures:***

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